PLANT GROWTH AND GRAZING PRESSURE

By

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DECLARATION

This thesis contains no material which has been submitted previously for a degree to any University. It contains no unacknowledged material which was the work of any other person, and where work was done in collaboration with others, due acknowledgement is given in the text.

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(Horacio L. Revora)

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SUMMARY

A project based on the 'systems concept' was developed to serve as a framework for integrating experimentation and simulation modelling, and to evaluate the suitability of simulation techniques for farm management research.

Experimental research techniques were used to assess the effect of grazing on plant productivity from pastures and crops.

The above ground net primary production (NPP) of two mixed temperate pastures continuously grazed by Merino wethers at two stocking rates was examined, through direct measurements of carbon dioxide exchange in an outside growth chamber. Increasing stocking rate resulted in a greater annual NPP as a consequence of increased net assimilation rates (NAR) in autumn and winter. It is suggested that these greater NARs resulted from the lower levels of leaf area index, permitting a more efficient utilization of the light environment. It was also shown that an increased stocking rate led to higher efficiency of forage utilization.

Six crops, including four winter cereals and two rapes, were rotationally grazed by Merino wethers at two intensities of defoliation and over four different periods of time, to assess the effects of grazing on regrowth rate, reproductive performance at flowering and grain yield at harvest. Intensity of grazing was the factor of prime importance in determining crop response. The rate of regrowth between the end of grazing and flowering was not affected by grazing. However, measurements of yield components at flowering showed that heavy grazing caused a significant reduction in number of live tillers and number of ears. In a general sense, grazing affected grain yield as a consequence of decline in the number of grain per head. Oats outyielded all the other crops, although it was found to be the crop most susceptible to grazing. Regression techniques were used to develop relationships between grazing parameters and

grain yield.

Some philosophical concepts underlying the systems approach are presented. In the same section the methodology of simulation is discussed in an agricultural context and some strategies for building models of bio-economic systems are advanced.

A simulation model of Merino breeding ewes grazing a pasture and a dual-purpose oats crop on a hypothetical farm situated in the Canberra environment was constructed, and its pasture submodel validated. The model was to serve the two-fold purpose of (i) gaining an understanding of the system's component parts and of the important interactions between them, and (ii) assessing the effect of such management variables as stocking rate, proportion of land allocated to the crop, proportion of sheep grazing on the crop and severity of crop grazing on the productivity of the system, as evaluated by a gross margin objective function.

Growth rates predicted by the pasture submodel were compared with actual rates derived from the pasture experiment. Good agreement between observed and predicted data was obtained for average values of variables, the matching of values for some other measures being less satisfactory.

Stocking rate was predicted to have a greater effect on economic returns than proportion of land under crop, although the system's response to changes in the latter became more sensitive as stocking rate increased. Crop grazing practices had no important effect on system productivity. The analysis of the response surface showed that the optimal region was bounded by 0 and 10 *per cent* cropping and by 7.5 and 15 sheep per hectare.

It was finally concluded that simulation modelling is a useful complement to physical experimentation since it indicates the areas on which to concentrate the usually limited research funds, and that it provides a framework for using results of research to solve decision-making problems at the whole-farm level.

CHAPTER 1:

INTRODUCTION

PLAN OF THESIS

INTRODUCTION

A farming enterprise is a human endeavour aimed at the production of essentials to satisfy the feeding needs of man and the personal goals of the producer. This implies that the prime concern of the agriculturalist must be the development of technology capable of combining adequate use of resources and financial success.

In a typical farming enterprise such as a grazing system, the concept of 'rational use of resources' can be best explained if looked at from the whole system viewpoint. For instance, the optimum combination of certain controllable resources - such as fertilizers, type of pasture and type and number of grazing animals - derived from short-term analytical research, may not hold for a different set of conditions. The existence of climatic variability makes it necessary to incorporate into the study the long-term effects of uncontrollable components - such as rainfall - to assess the true value of an *a priori* estimate of the optimum combination of resources. Besides, to achieve an adequate level of financial success, due account must be taken of the possible variations in the prices of inputs and outputs. Whereas price fluctuations can always be attached to the results of experimental research to make long-term inferences, it is seldom feasible to incorporate into a single grazing experiment all the components and samples of seasons which are required for the evaluation of farm management policies.

Thus it is clear that decision-making at the level of the farm enterprise is characterized by the extreme uncertainty of the environment on which the decision is to be made. Analytical techniques such as linear programming and dynamic programming have rather limited ability to handle the complexity and uncertainty of real world decisions (Hardaker 1967, Musgrave 1963). The use of simulation methods appears to be the most promising approach to the problem of decision-making under uncertainty, its appeal arising from the fact that there are no fixed rules on the form of the system model that is used. This enables the study of decision problems in relation to the full complexity and uncertainty of reality.

The overall objective of this study was to evaluate a sheep-cropping system by means of simulation techniques, in terms of the variables relevant to the profitability of such a system. Simulation was also envisaged as a framework for testing the results of experiments conducted on specific parts of the system.

A system model was developed to examine the consequences of varying stocking rate, the proportion of the farm under crop and crop grazing practices, and for making decisions about how the system should be managed.

The first experiment was conducted to evaluate the effect of stocking rate on net primary production of a mixed temperate pasture in the Canberra environment. The use of direct measurements of net photosynthesis enabled the direct calculation of the rates of the growth process in response to different defoliation regimes and over the entire length of the growing season. The results were subsequently compared with model predictions, in order to test the adequacy of the relationships used in the model to simulate pasture growth.

The second experiment was concerned with evaluating the effects of intensity and duration of grazing on grain yield of several dual-purpose winter crops. The results obtained were used to develop relationships between the defoliation parameters and grain yield, and the resulting equations were incorporated into the system model.

The formulation of the model was to serve two major practical purposes. Firstly, to get an insight into the system's component parts and the interactions between them. Secondly, to approximate system behaviour as accurately and simply as possible in relation to the original management problem. In fact different parts of the model were so designed that they actually served one or both purposes. For instance, the structures of the pasture and crop submodels include all the important internal and external variables likely to affect plant growth and the interrelationships between them and with the grazing animal, thus serving both purposes. On the other hand, for simplicity, some of the relationships used in the animal submodel are not meant to define exactly the biological mechanisms involved in a particular process, but simply provide an adequate transformation of input into output in terms of easily definable parameters.

In a general sense, given the readier availability of experimental data - collected by the author - for modelling and evaluating the principles of plant growth, the model was formulated so that it simulates the plant side of the system with more detail than the animal side. Nonetheless the results of experimentation with the complete model revealed a satisfactory balance among its components.

The model was finally used for evaluating system response to a number of management policies. The similarities between reality and model predictions - though not perfect - permitted an appreciation of the value of simulation for solving real-world decision problems.

PLAN OF THE THESIS

The thesis is divided into three parts, each concerned with a major phase of the study. Part A of the thesis comprises the present introductory Chapter and Chapter 2 where some relevant system concepts are discussed in an agricultural context. The methodology of simulation is also described, with a brief discussion on strategies of model building.

The next two Chapters, 3 and 4, constitute Part B of the thesis and contain the description and analysis of results of the pasture and winter-crops grazing experiments respectively. The first of these trials was designed with the assistance of Dr M. Freer, Principal Research Scientist of the Division of Plant Industry, CSIRO, Canberra; and conducted entirely by the author. The second experiment was designed and conducted in collaboration with Mr P.R. Dann, Research Officer of the Department of Agriculture of N.S.W. The author was responsible for the subsequent analysis of results and for the development of the relationships used in the crop submodel.

Part C of the thesis is composed of Chapters 5 and 6. Chapter 5 includes a description of a model of a mixed sheep-cropping farming system, named SSCFS. This system was selected because of the increasing importance of winter cropping in sheep production systems in Australian agriculture. In Chapter 6 a comparison is first made between the predictions of the pasture submodel and actual experimental results. The second part of this Chapter presents the results of a simulation experiment conducted with the complete model in order to study a specific management problem.

Finally, in Chapter 7 the most important aspects and conclusions of the study are summarized in relation to the original objective.

CHAPTER 2:

THE CONCEPT OF SYSTEMS APPROACH IN AGRICULTURE

GENERAL CONSIDERATIONS ON THE SYSTEMS APPROACH IN RELATION TO AGRICULTURAL RESEARCH

A systems approach is by its nature a philosophical concept elaborated by man for the analysis of living phenomena. It has been proposed that a 'system' may be simply a logical genus suitable to the treatment of wholes (Angyal, 1969), although in a scientific sense this word has varied connotations. The increasing interest in the problem of wholes has led to the formulation of certain general principles, best perhaps stated by the Gestalt psychologists. According to them wholes cannot be compared to additive aggregations at all, even given the fact that both are composed of several parts which are somewhat linked to each other. In additive aggregations summation of parts takes place and these parts function because of their inherent qualities. In wholes, the parts do not enter into a relationship merely by means of their inherent qualities but by means of their position in the system. In aggregates it is then significant that the parts are added; in a system it is significant that the parts are arranged (Angyal, 1969). In this discussion I shall follow the proposal of the above-mentioned author that the term 'whole' be reserved to designate the concrete 'organized object', while the organization itself, that is the way of arrangement of parts, should be called a 'system'.

One of the arguments for a systems approach has been that only such an approach will reveal the characteristic properties of the higher levels of organization which we denominate 'living systems'. Emery (1969) has also suggested that a systems analysis of living entities is likely to reveal the 'general in the particular'. The analysis of part systems (which could well be as simple as the relationship between two members) in cause-effect terms contributes to the systems approach in so far as it builds up the understanding of the whole. However, it is the analysis of the total system comprising them that is most likely to bring to light the alternative paths which may provide substitute feedback control systems.

A systems approach can then be viewed as a method of thinking whose adoption may enable the researcher to devise alternative ways of arrangement of parts (control systems). The design of such control systems and the assessment of their performance in reality are examples of the way in which the foregoing philosophical concepts may be applied to research in agriculture.

A farm is a typical production system (Morley and Spedding, 1968), within which a number of subsystems of varying complexity can be identified such as soil, individual plants, plant communities, animals and production units. Agricultural activities are characterized by the fact that man is attempting to control bio-economic systems to achieve some objective which is predominantly economic in nature. In so doing he is confronted with many uncertainties, for example weather variability and market fluctuations. Such uncertainties emphasize the need for having some degree of knowledge of the likely response of the system to modifications in the state of some of its components, whether these modifications are due to exogenous factors or control measures.

At this point it may be argued that scientific method has always been concerned with the analysis of causal relationships. This being true, it is important to note that these relationships have usually involved only a few members of the system. These members, in turn constitute a subsystem which in its simplest form may be composed of only two members (relata). Even complex relationships can and usually have been analysed at the level of subsystems of two members.

The distinguishing feature of a systems approach is that its objective is the understanding and rearrangement (if necessary) of the whole. That is, a systems approach attempts to incorporate in the study all the elements which influence a decision or response, or the elucidation of some phenomenon, within defined boundaries (Morley, 1972a). Morton (1964) has expressed this idea in other terms by suggesting that systems research is no more nor less than scientific method itself consciously applied to complex organizations in order that no important factor be overlooked.

The two main activities involved in systems research are analysis and synthesis which can be equated to principles of disassembly and assembly respectively. Systems analysis is concerned with the qualitative and quantitative specification of the component parts within the system boundary, and the necessary identification of events occurring among the interrelated subsystems. Systems synthesis is concerned with the application of the knowledge gained from the analysis phase, in order to modify the original system or to devise entirely new systems. This may require that a new set of components be specified (systems design) and/or the relationships among components be modified (systems control or management). No further detailed considerations of these topics will be presented in this thesis as they have been previously dealth with by several authors (Anderson, 1974; Dale, 1970; Wright, 1970, 1971).

Methodology of simulation

The construction of models, the use of simulation techniques and computers are aids to a systems approach, but they are not necessary features of it. The term 'simulation' like 'system' is sometimes a source of confusion due to the lack of an accepted terminology. According to Naylor (1966) simulation is a technique 'that involves setting up a model of a real situation (system) and then performing experiments on the model.' That is, simulation is basically a two-phase operation including modelling and experimentation. The real system is replaced by an analogous, but abstract, system in order to overcome problems of physical experimentation.

In the fields of engineering, government and defence, systems simulation is almost a routine tool for the development of techniques of management. However, in agriculture, simulation has only recently been applied by research workers and the process of integration with conventional research techniques seems to have been quite slow. Factors like the absence of estimates of many parameters, instability of such parameters and the lack of recognition of the need for such estimates may have prevented the occurrence of a more rapid integration (Morley 1972b).

Despite its brief history the process of biological simulation has become fairly standardized although details may vary when applied to different disciplines. The description of all the steps involved in the process of simulation is a large task that has been adequately performed by Gordon (1969) and Naylor *et al.* (1966), and in a specifically agricultural context by Dent and Anderson (1971).

For the purpose of the present discussion a graphical aid will be used to focus attention on the integration of simulation techniques with the more traditional method of agricultural research. This will also serve as a continuation of the foregoing section.

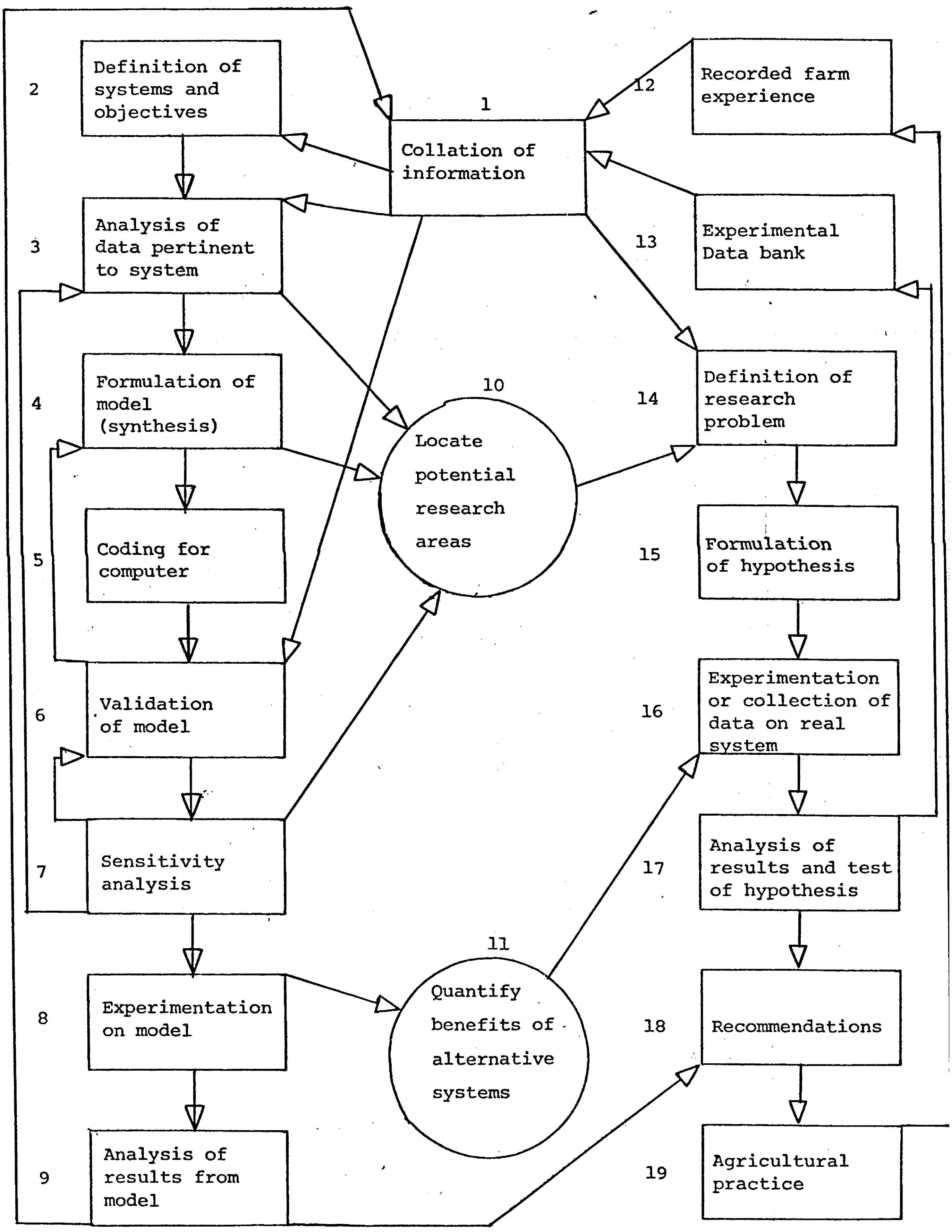
Figure 2.1 shows on the left hand side a typical sequence in the development of a simulation study (blocks 2 to 9) and on the right hand side a brief description of a conventional way of applying the scientific method in agricultural research. An important feature in this diagram is the occurrence of feedback processes, which are characteristic of the almost cyclic nature of many simulation studies.

Blocks 10 and 11 are the intermediate steps through which simulation and conventional research may be integrated. These interactions may prove to be most useful to both directors of research (block 10) and research workers concerned with the possible applications of their findings to farm practices (block 11). The lines linking blocks 9, 1 and 14 show the route by which simulation may influence the initiation of experimental research on real systems.

Commencing a simulation study may be a rewarding experience since the analysis and synthesis phases may already reveal insufficient knowledge (links 3/10 and 4/10) of the system and so suggest potential research projects to overcome these shortcomings (link 10/14). Sometimes it may be a rather frustrating activity if progress beyond block 3 is prevented.

The proposed role of simulation as an aid to decision-making problems is exemplified in block 11. Once a model has been constructed and validated it can be used to evaluate the possible

Figure 2.1: Diagrammatic representation of the possible interaction of systems simulation and conventional research in agriculture (From Anderson and Dent 1972).



output of new systems. Some degree of further experimentation with the real system may be necessary to test the suitability of the proposed control measures in practice (Links 8/11/16). A more daring approach would be following the route 9/18, although it may prove to be useful in feasibility studies in which recommendations based on a thorough examination of the problem (by means of simulation) are likely to be more successful than those based on experience, intuition or informal appraisal.

Strategies of model building in relation to bioeconomic systems

Modelling is just a phase of simulation which consists of developing a mathematical model of a system suitable for operation on a computer. In fact mathematical models only represent one of the types in which models can be classified.

Ackoff, Gupta and Minas (1962) distinguish between three basic kinds of models: iconic, analogue and symbolic. Iconic models are similar to the real system in that the relevant properties are represented by those properties with only a transformation in scale. The plot of the agronomist can be considered as an iconic model of the real pasture or crop system. Analogue models are based on the use of one property to represent another. There are not many examples of the use of analogue models *per se* in agriculture but the mechanical mowing of pasture as a substitute for animal grazing is representative of the approach. Symbolic models are those in which properties are represented by symbols and if those symbols represent quantities they are called quantitative mathematical models.

There are four stages involved in symbolic modelling. Firstly the model must be designed or given a structure. Secondly, the mathematical equations must be prepared for the computer (programming). Thirdly, values are assigned to the independent variables and the computer uses the program to determine the outcome (simulation). Finally, the output of the model must be compared with real systems if data are available (validation). If the output is unreal or inconsistent, the model cannot be considered to be realistic, and it will need to be redesigned. When the output is realistic, a sensitivity analysis is then performed to evaluate the relative importance of the variables in the model.

The structuring of the model is the first and the most important step and it will be the result of the purpose of the model and the level of knowledge of the processes involved. One characteristic of any complex system is its dynamic behaviour which is the result of the interactions between its components which lie within a boundary that defines and encloses the system.

Formulating a model of a system should then start from the question: "where is the boundary, that encompasses the smallest number of components, within which the dynamic behaviour under study is generated?"

The concept of state-determined system (Ashby, 1960) may be helpful in deciding what variables to include in the model. It states that the variables selected must define the state of the system sufficiently fully to ensure that, within the desired practical limits of accuracy, the changes of state depend only on the current state and not on how it was reached.

It might be also helpful to recognise that in biology various levels of knowledge may be distinguished, characterized by the level of organization within the systems and by the relaxation times of the phenomena, i.e. by the time taken to recover from small disturbances. Roughly speaking the range of relaxation times in biological phenomena involves a factor of 10^7, from seconds to years (de Wit, 1969). The areas of biological study in this spectrum of relaxation times concern molecule, cell structure, whole cells, tissues, organs, individuals, populations and communities.

Simulation modelling provides a means for joining two levels of knowledge, and in this way we may devise a strategy of model building whereby the level with the shorter relaxation time is the "explanatory" level, explaining what happens at the level with the longer relaxation time.

On the other hand it does not appear to be wise to attempt encompassing in a model three or more levels of knowledge since the levels of detail needed would be so much that the model would grow beyond manageable size, being also likely to outgrow the computation ability of present day computers.

How these concepts could be applied to a strategy of model building, with particular reference to the problem of modelling plant growth, may be better explained by reference to some practical examples. If the ultimate objective of a model is to examine the process of plant or crop growth, then those variables included in the "explanatory" level can be simulated in terms of rate equations to explain the outcome of the level with the longer relaxation time (de Wit, 1969). This means that the rates of photosynthesis and respiration, growth and development measured in physiological experiments can be used to predict plant growth.

An example of this kind of model is that of Paltridge (1970), in which an attempt is made to simulate the growth of an organism which is only composed of leaves and whose main characteristic is that it can make use of the solar radiation and the atmospheric carbon dioxide to increase its weight and size. Provision is also made to allow the organism to build up a certain architecture similar to that of a pasture canopy.

However, if we are dealing with a farming system, and particularly with a grazing system, our objective would then be to examine the output of such a system through the evaluation of different sets of managerial policies or as the result of distinct environmental conditions. Pasture or plant growth then becomes only one more component of the model that interacts with the others to produce a certain result which will be basically evaluated in terms of profit.

It is, for example, the quality and quantity of herbage on offer that influences the rate of animal intake, and not the rate of photosynthesis of the plant. If we can then base our model on some characteristic of the process of growth, e.g. relative growth rate or growth rate, which bears some relationship with the environmental variables and the plant variables as well as with the grazing animal, we will have produced a model on which the variables included are sufficient to account for the main processes operating in such a system, so that any change of state can be defined based on the current state and not on how it was reached.

Several models that have been formulated on this basis can be quoted.

Pasture growth at Armidale, N.S.W. has been calculated by two regressions relating the relative growth rate (above and below ground) to weekly mean soil temperature and soil moisture. Adjustments to these values of relative growth rate are made by a seasonal coefficient for pasture age and a stepped function taking into account the effect that large values of leaf area index has on growth rate due to the shading of the lower leaves (Vickery and Hedges, 1972).

In the absence of suitable data to relate sward growth rate to light and temperature, Wright (1970) opted to develop a series of time-dependent relationships. Sixteen polynomials were used to specify the relationship between potential pasture growth and available herbage at different times of the year. These relationships were specific to pastures in the New England region.

Pasture growth in the model EIEIO (Christian *et al.*, 1973) is generated by a series of logistic curves. The parameters of these curves are devised from specified relative growth rates and ceiling yields for each 10 day period of the year. Instead of using a soil moisture budget in this model, different sets of relative growth rates and ceiling yields are used for different years.

PART B

EFFECTS OF GRAZING ON PLANT PRODUCTIVITY

CHAPTER 3:

EFFECTS OF GRAZING ON NET PRIMARY PRODUCTION OF A *PHALARIS TUBEROSA* - *TRIFOLIUM SUBTERRANEUM* PASTURE IN A TEMPERATE ENVIRONMENT

INTRODUCTION

Net primary production (NPP) of a plant community is defined as the biomass or biocontent (total energy content) which is incorporated into it during a specified time interval, less that respired. This quantity has also been called net assimilation or apparent photosynthesis (Milner and Hughes 1968). The measurement of this parameter provides a starting point for describing the functional aspects of an ecosystem, because all organisms of a community, except the primary producers, ultimately depend upon the energy supplied by photosynthetic plants.

Above ground plant production has usually been assessed by measuring the increase in standing crop during the growing season, and descriptions of the methods proposed can be found elsewhere (Odum 1960, Olson 1964). These techniques of measurement for ungrazed or lightly grazed swards may provide a satisfactory estimate for a monospecific crop where individual plants mature together and where little plant tissue dies before maturity. However, for a number of reasons, the measurement of standing crop does not provide a valid approximation of the productivity of mixed grazed pastures.

Firstly, in a mixed stand, the peak standing crop for individual species may be attained at different times (Wiegert and Evans 1964, Hutchinson 1971) and, if this is the case, peak seasonal values will underestimate plant production. Secondly, death and subsequent decomposition of plant tissue may occur at any time throughout the growing period because of such factors as aging, frost damage, moisture stress and trampling. The growth represented by such amounts of plant material would not be taken into account by standing crop determinations. Thirdly, domestic grazing animals may consume a large proportion of the herbage produced and this does not, therefore accumulate as an increase in herbage available. Finally, important interactions may occur between the grazing animal and plant growth; lenient grazing may increase productivity by increasing tillering and leaf area, while severe grazing may be detrimental to growth.

The traditional technique for measuring plant production in grazing systems is the use of open and closed quadrats (Linehan *et al.* 1947, 1952, Milner and Hughes 1968). Provided that both live and dead plant material are measured and rate of disappearance of dead herbage is determined, this method does provide satisfactory estimates of net primary production. However, criticisms of this approach are that shoot growth is calculated in the absence of the grazing animal and that the method of exclosure imposes a different set of environmental conditions on the plant community (Cowlishaw 1951, Dobb and Elliot 1964).

Other methods for evaluating NPP, whereby the shortcomings of the exclosure technique can be overcome, have also been proposed (Milner and Hughes 1968, Vickery 1972) but, as yet, have not been widely used. In one of these methods, NPP is determined directly from measurements of carbon dioxide exchange by the plant community.

In the experiment reported in this chapter, such measurements were made, under partially-controlled environmental conditions, on sods from two pastures set stocked at 7 and 30 sheep ha^{-1}, in order to assess their net primary productivity. These measurements were repeated at intervals throughout the year and, since they were made with the sods exposed to natural sunlight, in temperature conditions simulating those of the field and with water supply non-limiting, the results are assumed to represent the potential NPP of these pastures in the Canberra environment, as determined by the quantity of photosynthetic tissue resulting from the different defoliation regimes.

MATERIALS AND METHODS

Site

The experiment was conducted between July 1974 and June 1975 on two adjacent plots located in the same area as that of the experiment described in Chapter 4. The plot sizes were 2.4 ha and 0.8 ha and they were sown in 1958 with a mixture of *Phalaris tuberosa* and *Trifolium subterraneum*. Since 1962 they had been continuously grazed at stocking rates of 7 and 30 sheep ha^{-1} respectively. During the 9 years following establishment, the pastures received a total of 2000 kg ha^{-1} superphosphate but no further fertilizer applications since 1968. Separate tests have shown no response to additional superphosphate on similar pastures during the intervening period.

Sampling procedure

Two cylindrical sods, 0.1238 m^2 surface area and 0.23 m deep were extracted from each pasture at three-weekly intervals from 3 July to 7 Decmeber and from 6 March to 20 June. Low soil moisture and senescence of annual species caused growth to cease soon after the December samples were taken, and therefore no more sods were dug until regrowth started in early March.

Since the measurements of carbon dioxide exchange lasted 24 hr and only one growth chamber was available, replicate samples were taken on alternate days so that the samples from different treatments could be run on consecutive days, to minimize differential weather effects.

The sods were extracted from 60 x 60 cm sites which had a herbage yield equal to the mean value for the plot. The mean value was determined from 25 readings taken with an electronic capacitance pasture meter (Jones and Haydock 1970). These readings were randomly distributed over the plot, along imaginary lines which traversed each plot four times.

Measurements

All sods were removed at the same time, between 1500 and 1700 hours, on the day prior to the growth chamber measurements. At 0900 hours the following day, the sod was placed in an outdoor glass chamber, 1.37 x 0.89 x 0.51 m, and the rate of carbon dioxide uptake or release was measured at 1 minute intervals for 24 hr. A fully automatic apparatus (designed by Mr J.W. Birch) was used for these measurements and for controlling the temperature and humidity of the air blown into the chamber.

This apparatus was originally designed to measure photosynthesis and transpiration in a controlled environment. It consists of an infra-red gas analyzer, a humidifier-dehumidifier which enables the dewpoint of the air to be adjusted between 2 and 20^{o}C, a dewpoint hygrometer to measure water vapour concentration, a temperature controlling device, several sets of lights and an electronic unit. The functions of this unit are (i) to drive all the individual instruments; (ii) to receive information from sensors and to adjust the levels of the environmental variables in accordance with those of the programmed patterns and (iii) to record all readings from instruments and sensors on a 12-channel recorder and/or on a paper tape. Four environmental parameters (temperature, humidity, light and carbon dioxide concentration) can be varied manually by switches or automatically by prewired program cards. The program facility enables a sequence of experimental conditions to be repeated identically. Up to 25 predetermined steps can be built into one program. Each step may switch in different values of light intensity etc. The period of each step is independent and can range from 0.5 min to 2 hr.

All measurements in this experiment were made under natural lighting. Both total solar radiation and photosynthetic active radiation(PAR) were recorded. In order to standardize conditions, sunny days were chosen for all runs. If during a period of measurements, the day became overcast, the run was stopped and then re-started the following morning.

The chamber temperature was varied hourly according to the mean diurnal temperature pattern for the month concerned, which was calculated from a 36 year series of temperature records (see Table 4.1). A different prewired program card was used for each month of the experiment.

Air humidity in the chamber was kept constant at the level of air with a $2^{\circ}C$ dew point. Water availability was also standardized by watering the sods to field capacity on the day prior to measurements.

At the end of each run, the sod was defoliated and the carbon dioxide released by debris, soil and fauna was measured for 2 hr in the dark.

The herbage removed was sub-sampled for sorting into green and dry components. Each of these fractions was then oven-dried at $100^{\circ}C$, weighed and ashed at $600^{\circ}C$ to determine the weight of organic matter. Leaf area was measured on the basis of green herbage, including leaves, sheaths and green stems, using an electronic leaf area meter.

After the measurements of soil respiration, the sods were washed free of soil. The root material was then dried, weighed and a sub-sample ashed to determine the weight of organic matter.

Calculations

The infra-red gas analyzer provided data on the carbon dioxide (CO_2) concentration of the air entering and leaving the chamber. The difference between these two readings indicated the amount of CO_2 being absorbed or released by the sward. From this, carbon dioxide exchange (CO2EX) in mg CO_2 per g plant weight and per hour was calculated by the computer program using the following equation:

$$\text{CO2EX} = \text{CO2DIFF*FLO*(44.0/VOLAIR)*0.06/DMWEIT} \qquad (1)$$

where CO2DIFF = difference in CO_2 concentration (ppm) between incoming and outgoing air flows

FLO = air flow rate (1 min^{-1})

VOLAIR = volume of CO_2 containing 1 mol of gas at a given temperature and pressure (assumed to be 720 mm)

44.0 = weight of 1 mol CO_2 (mg)

DMWEIT = weight of above ground green plant material (g DM)

Respiration rates during the night were found to remain almost constant from the time when the air temperature in the chamber fell to its minimum programmed value, until it began to rise again in the morning after sunrise. Therefore, to simplify calculations, dark respiration rates were not based on hourly readings but derived from the readings recorded in the hour corresponding to the middle of the dark period. Different durations of the period of minimum temperatures were programmed - from 4 to 6 hr - to account for seasonal variations in the length of the night.

The hourly rates of net photosynthesis and respiration calculated in equation (1) were then converted to actual rates by adjusting them for the rate of carbon dioxide evolution from the defoliated sod. The carbon dioxide assimilated by crops is supplied by downward transfer from the atmosphere and by upward transfer from the soil. As calculated in equation (1), the figures of carbon dioxide exchange do not take into account the carbon dioxide released by the soil. Hence, when these figures are positive, net photosynthesis is underestimated and when they are negative, the rate of plant respiration is overestimated. Therefore, the values of carbon dioxide evolution from the soil must be added to the results calculated from equation (1) and the equation used for this correction was:

CO2EX = (CO2EX*DMWEIT + SOILRES)/DMWEIT (2) where SOILRES = carbon dioxide released by the soil (mg hr^{-1}).

Daily net assimilation rate of the above ground parts of the plants (tops), in mg CO_2 g^{-1} day^{-1}, was calculated as the algebraic sum of the hourly values of net photosynthesis and respiration obtained from equation (2). Daily carbon dioxide assimilation by the tops, in g CO_2 m^{-2} day^{-1}, was calculated as the product of net assimilation rate and the yield of green organic matter (g m^{-2}).

The energy incorporated into the system by photosynthesis (kcal m^{-2} day^{-1}) was calculated, using the conversion factor 2.7 kcal g^{-1} CO_2 (Yocum *et al.* 1964). The energy assimilation figures were then converted to dry matter gain, assuming an energy content in the dry matter of 4.3 kcal g^{-1}.

RESULTS

Least squares analysis of variance was used to assess the effect of time and stocking rate on net assimilation rate (NAR), carbon dioxide assimilation, organic matter yields of green, dead and total herbage, organic matter yield of roots, leaf area index (LAI) and ratio of green to dead herbage.

Net assimilation rate

Similar seasonal trends in NAR were observed for both stocking rate treatments during winter and spring of 1974. A continuous increment in NAR occurred during the winter months until a peak level was reached in early spring, thereafter remaining relatively constant for the rest of the season. With the onset of summer, there was a drop in NAR at 7 sheep ha^{-1}, whereas at 30 sheep ha^{-1} NAR fell only slightly (Fig. 3.1). During the winter months in both years, heavy grazing resulted in an average NAR higher than that of lenient grazing, the mean difference being 68.3 mg CO_2 g^{-1} day^{-1}.

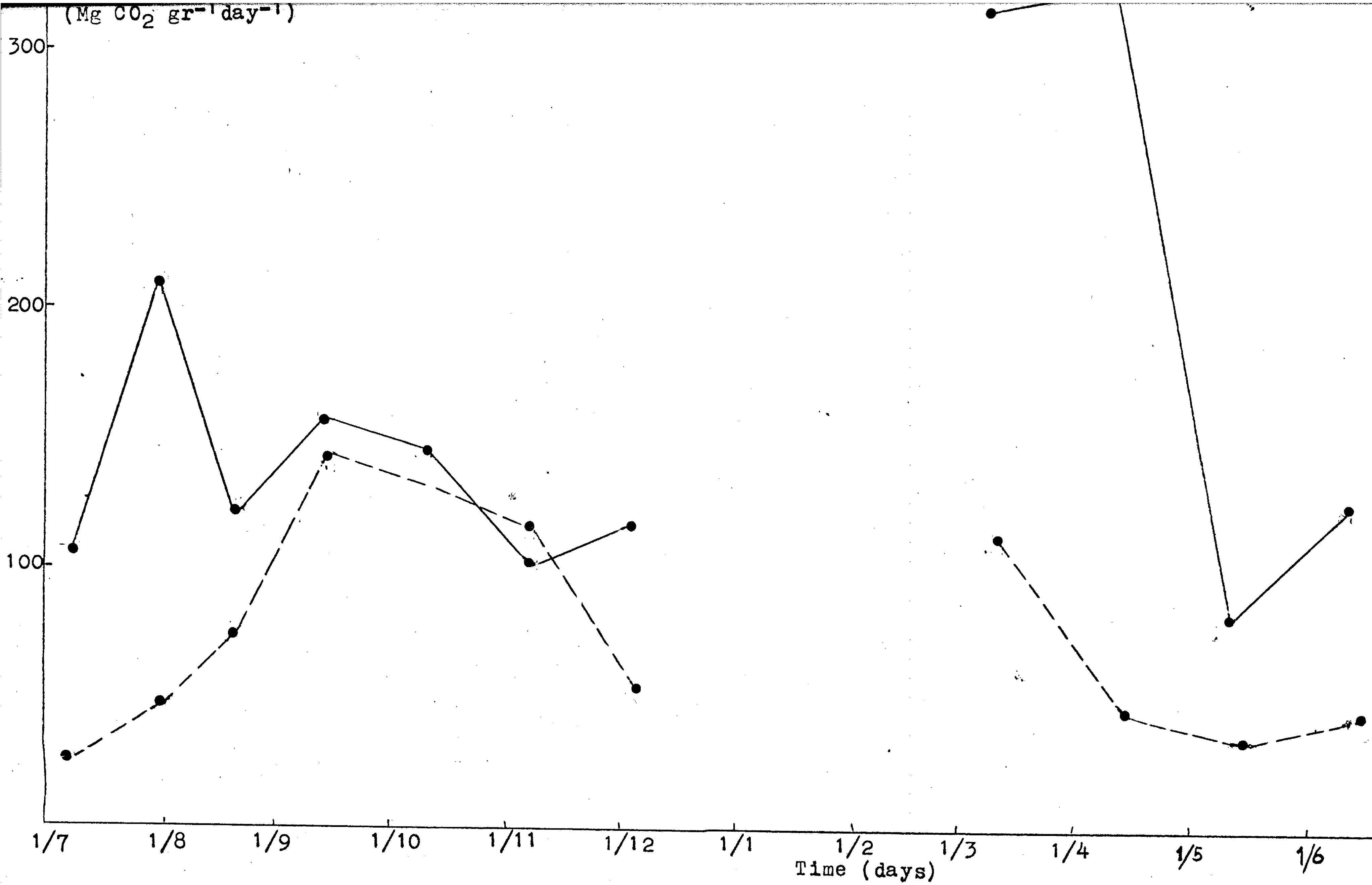


Figure 3.1: Seasonal trends of NAR as based on green organic dry matter for two pastures composed of Phalaris tuberosa and Trifolium subterraneum set stocked at 7 sheep per ha (●---●) and 30 sheep per ha (●—●).

The measurement of NAR made for the 30 sheep ha^{-1} treatment at the second sampling (see Table 3.1 for 1 August) is regarded by the author as abnormally high. This figure is based on only one sample since a breakdown in the growth chamber equipment invalidated the results of the replicate sample. Therefore, this value was not included in the comparison between treatments made above for the winter months.

In the autumn, both treatments showed a general decline in NAR as the season progressed. At 30 sheep ha^{-1} NAR reached its highest level in March, whereas at 7 sheep ha^{-1}, the NAR values did not surpass those recorded in spring. The mean NAR for this period at 30 sheep ha^{-1} was 177.2 mg CO_2 g^{-1} day higher than at 7 sheep ha^{-1}.

Over the 52 weeks of the experiment, heavy grazing resulted in a NAR significantly higher ($P<0.001$) than lenient grazing, the difference being 88.7 mg CO_2 g^{-1} day^{-1} (Table 3.1).

Carbon dioxide assimilation by the tops

The seasonal trends of carbon dioxide assimilation followed a similar pattern to that of NAR. There was a significant seasonal effect ($P<0.01$) on the rates of carbon dioxide assimilation. Maximum levels of assimilation were attained in late spring for both grazing treatments, these levels being more than double those recorded in autumn and winter (Table 3.1).

When stocking rate treatments were compared over the 52 week experimental period, no significant difference was found between the mean values for carbon dioxide assimilation. However, in early autumn carbon dioxide assimilation at 30 sheep ha^{-1} was 68.6 *per cent* greater than at 7 sheep ha^{-1} (Figure 3.2).

TABLE 3.1: The influence of time of year and stocking rate on net assimilation rate and carbon dioxide assimilation of a *Phalaris tuberosa-Trifolium subterraneum* pasture. Measurements were taken from 3 July 1974 to 3 June 1975 at three-weekly intervals.

Sampling Period	Net assimilation rate (mg CO_2 g^{-1} day^{-1})			CO_2 assimilation (g CO_2 m^{-2} day^{-1})		
	Stocking rate (sheep ha^{-1})			Stocking rate (sheep ha^{-1})		
	7	30	Mean	7	30	Mean
3-10 July 1974	27.8	106.0	66.9	5.0	8.1	6.6**
31 July-1 August	48.0	211.7	129.9	10.4	15.3	12.8
20-21 August	75.0	119.6	97.3	13.5	11.5	12.5
12-18 September	144.3	159.9	152.1	21.1	22.6	21.9
8-15 October	133.1	146.5	139.8	15.4	28.7	22.1
4-11 November	117.1	101.6	109.4	26.8	25.3	26.0
2-7 December	56.1	119.8	88.0	22.5	33.5	28.0
6-14 March 1975	113.4	317.3	215.4	13.7	16.8	15.2
8-18 April	46.9	327.6	187.3	4.9	14.2	9.5
7-16 May	36.1	83.1	59.6	5.3	7.1	6.2
10-20 June	47.7	128.1	87.9	5.0	4.9	5.0
Means	76.9*	165.6	n.s.	13.1 n.s.17.1		

* SED between stocking rate means for NAR = 24.1

** SED between means of each sampling period for carbon dioxide assimilation = 5.9

n.s. No significant differences between means.

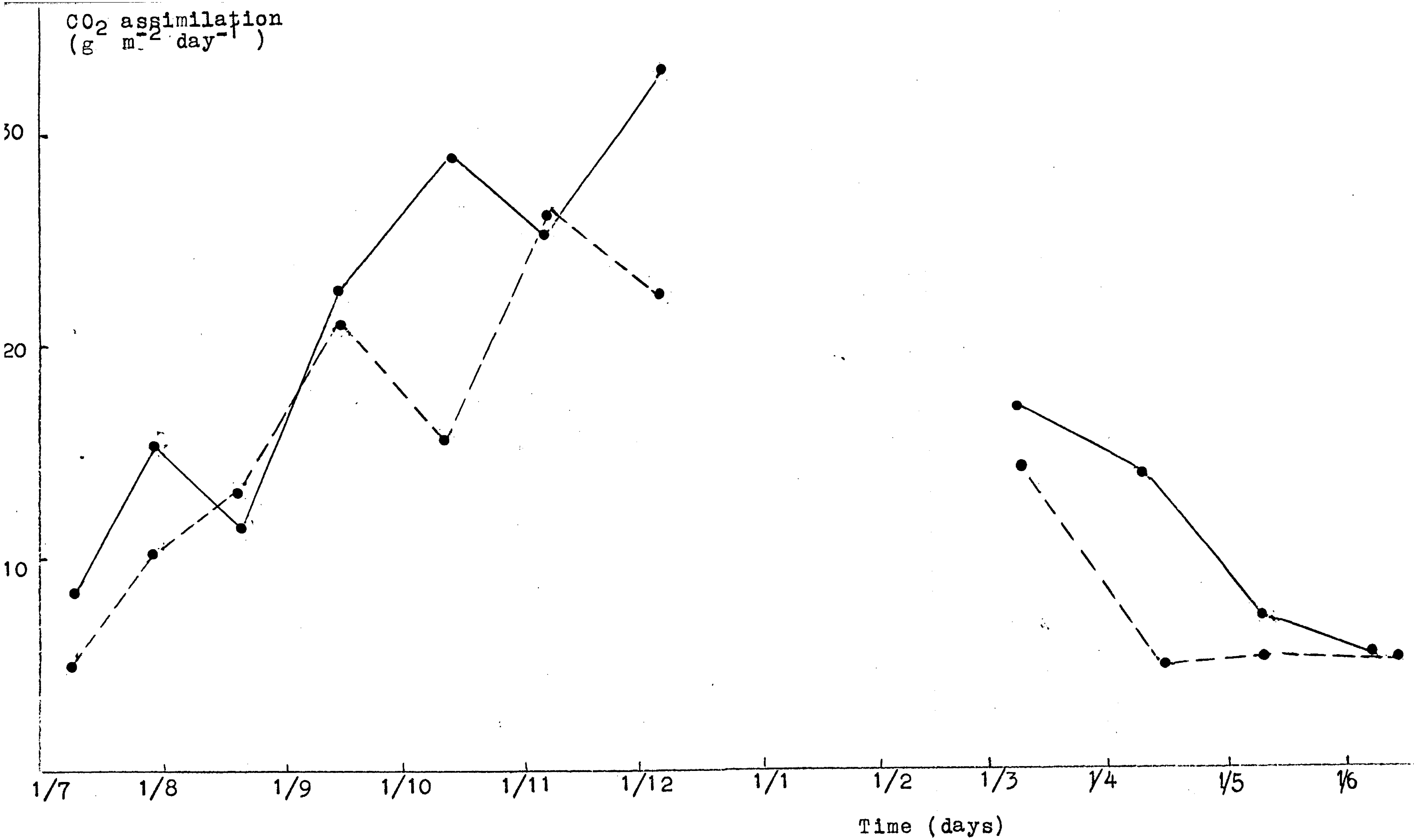


Figure 3.2: Seasonal trends of CO_2 assimilation for two Phalaris tuberosa and Trifolium subterraneum pastures, set-stocked at 7 sheep per ha (●- -●) and 30 sheep per ha (●—●).

Green and dead dry matter yields of herbage

There were significant seasonal trends in the amounts of both green and dead plant material present ($P<0.01$ and $P<0.001$ respectively) which are shown in Figure 3.3.

Yields of green herbage at both stocking rates reached a similar maximum value in late spring, with the lowest yield being recorded at the end of the experiment in early winter 1975. At this time, the lightly grazed pasture yielded only 459 kg DM ha^{-1} more than the heavily grazed pasture. At the start of the experiment, however, the difference was 1038 kg DM ha^{-1}, and this difference remained relatively constant throughout the winter months. The analysis of variance showed a significant difference ($P<0.05$) in mean yield of green herbage, which amounted on average to 470 kg DM ha^{-1} (Table 3.2).

The effects of time and stocking rate on dead herbage yields were highly significant ($P<0.001$). At 7 sheep ha^{-1}, dead plant material decreased continually from the beginning of August until November and then increased rapidly, to reach a peak yield at the same time as that for green herbage. For the rest of the experiment, dead herbage yields remained at a level slightly lower than that attained in spring (Figure 3.3). At the higher stocking rate there was little seasonal variation in dead herbage, except in January when the increase was two-fold as a result of the drying of green herbage during the previous month. The average amounts of dead herbage over the 52 weeks of the experiment were 3098 and 842 kg ha^{-1} for the low and high stocking rate treatments respectively (Table 3.2).

On these continuously grazed pastures, the yields of green and dead herbage do not represent herbage production, but only that part of the above ground plant material which is not consumed by herbivores or lost

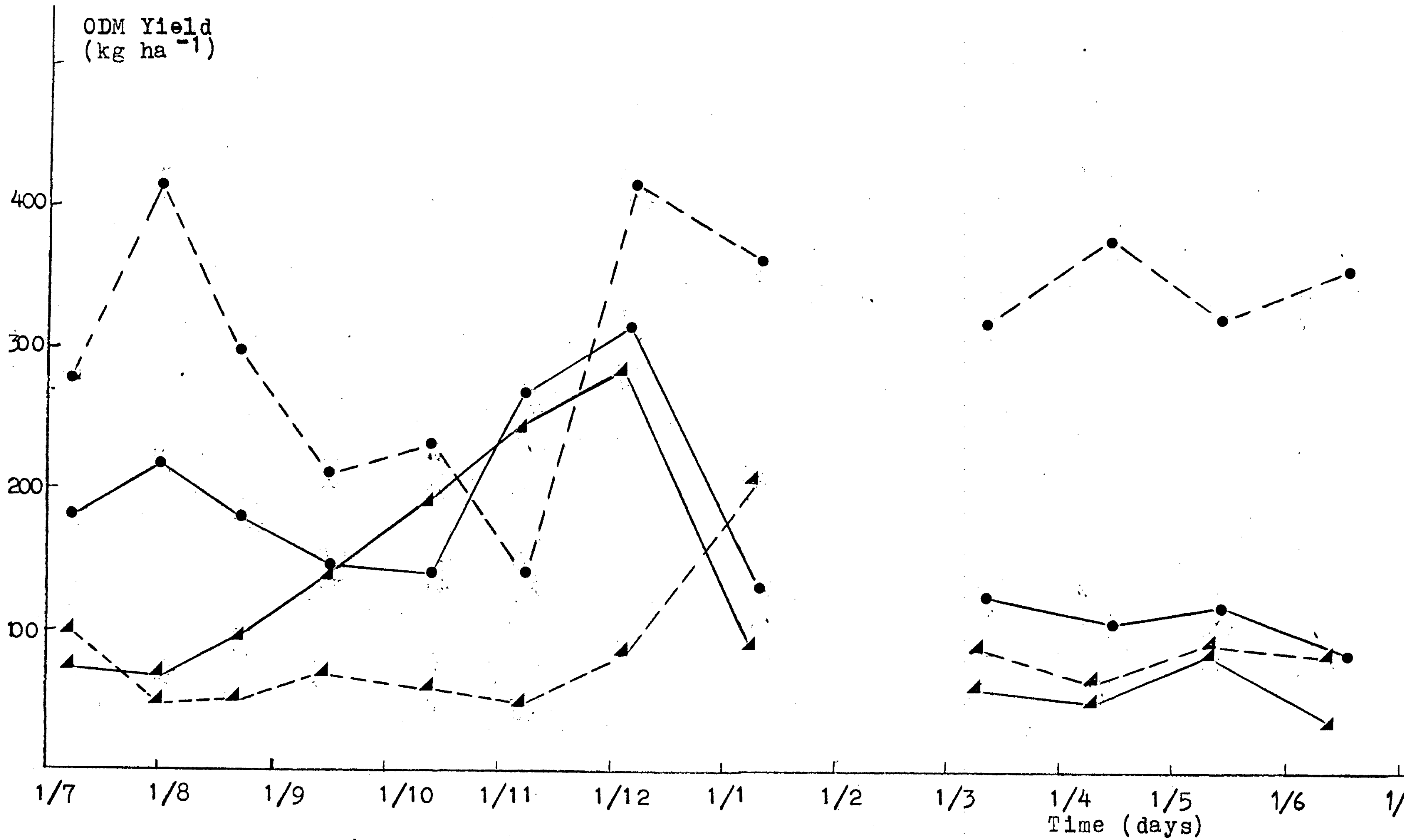


Figure 3.3: Green (——) and dead (---) organic dry matter yields of two Phalaris tuberosa - Trifolium subterraneum pastures set stocked at 7(●) and 30(◢) sheep per hectare.

TABLE 3.2: The effect of season and stocking rate on green and dead organic matter (OM) yield and root biomass of a *Phalaris tuberosa-Trifolium subterraneum* pasture.

Sampling period	Weight of green OM (kg ha^{-1})			Weight of dead OM (kg ha^{-1})			Root biomass (kg ha^{-1})		
	Stocking rate (sheep ha^{-1}) 7	30	Mean	Stocking rate (sheep ha^{-1}) 7	30	Mean	Stocking rate (sheep ha^{-1}) 7	30	Mean
3-10 July 1974	1841*	777	1296†	2769*	1016	1893†	12367*	9297	10832†
31 July-1 August	2159	721	1440	4158	499	2328	12423	6543	9483
20-21 August	1797	964	1381	2971	539	1755	7520	7431	7476
12-18 September	1439	1416	1428	2106	710	1408	8913	7031	7972
8-15 October	1396	1951	1674	2320	624	1472	8784	6268	7526
4-11 November	2658	2456	2557	1408	490	949	8497	5291	6894
2-7 December	3164	2865	3014	4170	863	2516	9709	6607	8158
9-10 January 1975	1314	920	1117	3600	2086	2843	9136	7520	8328
6-14 March	1233	597	915	3153	881	2017	8756	5452	7104
8-18 April	1045	489	767	3758	676	2217	7589	4453	6016
7-16 May	1172	858	1015	3207	873	2040	8501	5028	6765
10-20 June	820	361	591	3557	849	2203	7996	6191	7094
Means	1668††	1198		3098††	842		9183††	6425	

* SED between time x stocking rate means are 621.5, 432.7 and 1263.8 for weight of green OM, dead OM and roots respectively.

† SED between means of each sampling period are 439.5, 306.0 and 893.7 for weight of green OM, dead OM and roots respectively.

†† SED between stocking rate means are 179.4, 124.9 and 364.8 for weight of green OM, dead OM and roots respectively.

by senescence or decomposition. They are presented here simply to help an understanding of the efficiency of carbon dioxide assimilation by the pasture and the fate of the energy incorporated into the system by means of photosynthesis.

Changes in root biomass

Both stocking rate treatments showed similar significant seasonal trends ($P<0.01$) which were opposite to those followed by the above ground plant material. Below ground plant weight was at a maximum in winter 1974, declined in spring and autumn and increased in summer (Figure 3.4).

The mean weight of organic matter in the roots at 7 sheep ha^{-1} was significantly higher ($P<0.001$) than at the higher rate, the difference being 2758 kg ha^{-1} (Table 3.2).

Seasonal variations in leaf area index (LAI) and its relationship with NAR

The values of LAI - the ratio of the area of the leaves to the area of the ground surface - measured in this experiment were generally low, when compared with results reported by other workers for similar types of pastures (Davidson and Donald 1957, Black 1963, Brown and Blaser 1968). These low figures are attributed to the folding of the sub clover leaves and consequent reduction in the measurable leaf area of the sample. It is estimated that the measured leaf area may have been up to 50 *per cent* less than the actual area, particularly in late spring when the swards contained a large proportion of sub clover leaves.

Nevertheless, there were significant seasonal trends in LAI ($P<0.001$). At the start of the experiment there was a decline in LAI particularly at 30 sheep ha^{-1}, but after the first month it began to rise, at a rate which prevailed for most of the spring. Changes at the lower rate were

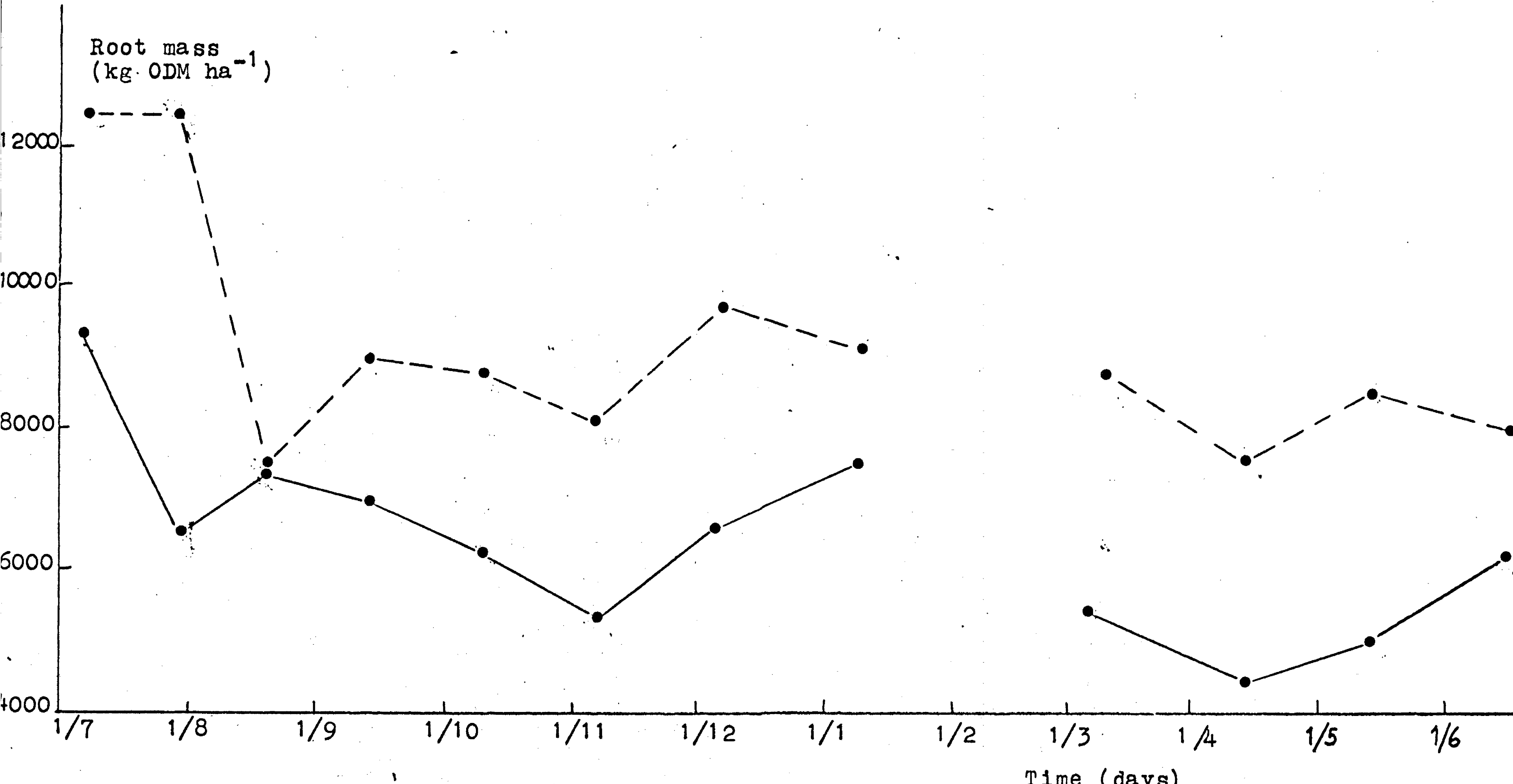


Figure 3.4: Seasonal changes in root biomass for two pastures composed of Phalaris tuberosa and Trifolium subterraneum set stocked at 7 (●---●) and 30 (●——●) sheep per hectare.

smaller but conformed to the same pattern.

LAI was at a maximum, for both treatments, in early summer, and fell to a minimum by mid-January. This steep decline (Figure 3.5) is the result of the drying off of the pasture, a process which is completed quite rapidly in the Canberra area once it has been triggered by high temperatures and soil moisture stress. In autumn there was an increase in LAI, but to a level which was lower than that recorded in the previous winter.

A comparison of mean LAIs over the 52 week experimental period showed a significant difference ($P<0.01$) of 0.6 units between stocking rates.

Least squares regression analysis was used to study the relationship between LAI and NAR. These two variables were found to be linearly and inversely related, and three regression equations were fitted, one for each season of the experiment (Figure 3.6). Equations (3), (4) and (5) below are those calculated for winter 1974, spring 1974 and autumn-winter 1975, respectively.

$$NAR = 197.5 - 48.83*LAI \quad (r^2 = 0.67) \qquad (3)$$

$$NAR = 218.8 - 32.21*LAI \quad (r^2 = 0.43) \qquad (4)$$

$$NAR = 373.8 - 336.7*LAI \quad (r^2 = 0.56) \qquad (5)$$

The responses of NAR to changes in LAI in winter and spring were similar, as shown by the regression coefficients in equations (3) and (4). However, during autumn, NAR was apparently much more sensitive to changes in LAI.

Relationship between LAI and weight of green herbage

This relationship was first examined for each stocking rate separately over the whole experimental period, but, as no significant difference was found between the treatments, the data were pooled and the following

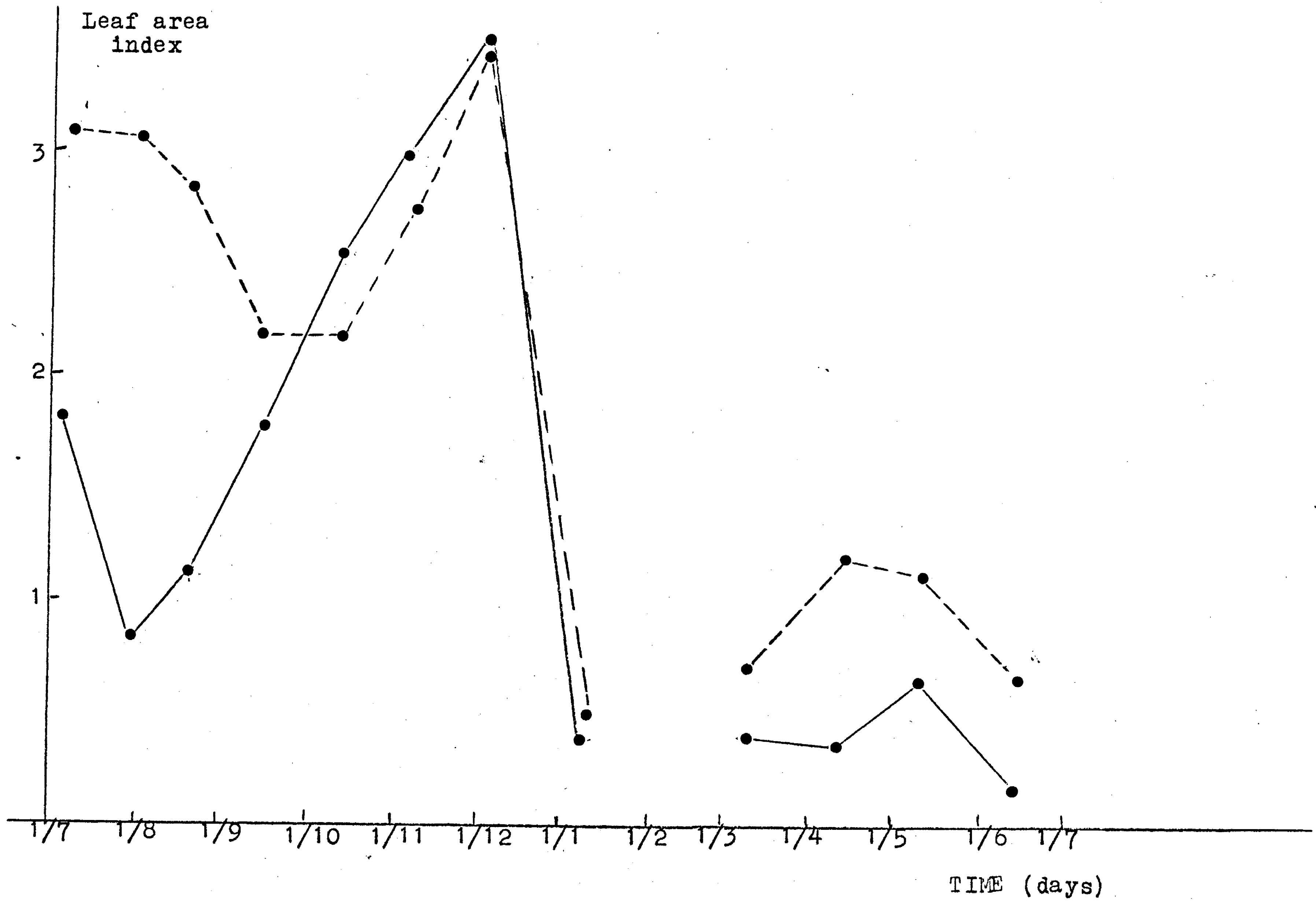


Figure 3.5: Seasonal Variation of LAI ofaPhalaris tuberosa-Trifolium subterraneum pasture grazed at 7(●----●) and 30 (●—●) sheep per ha.

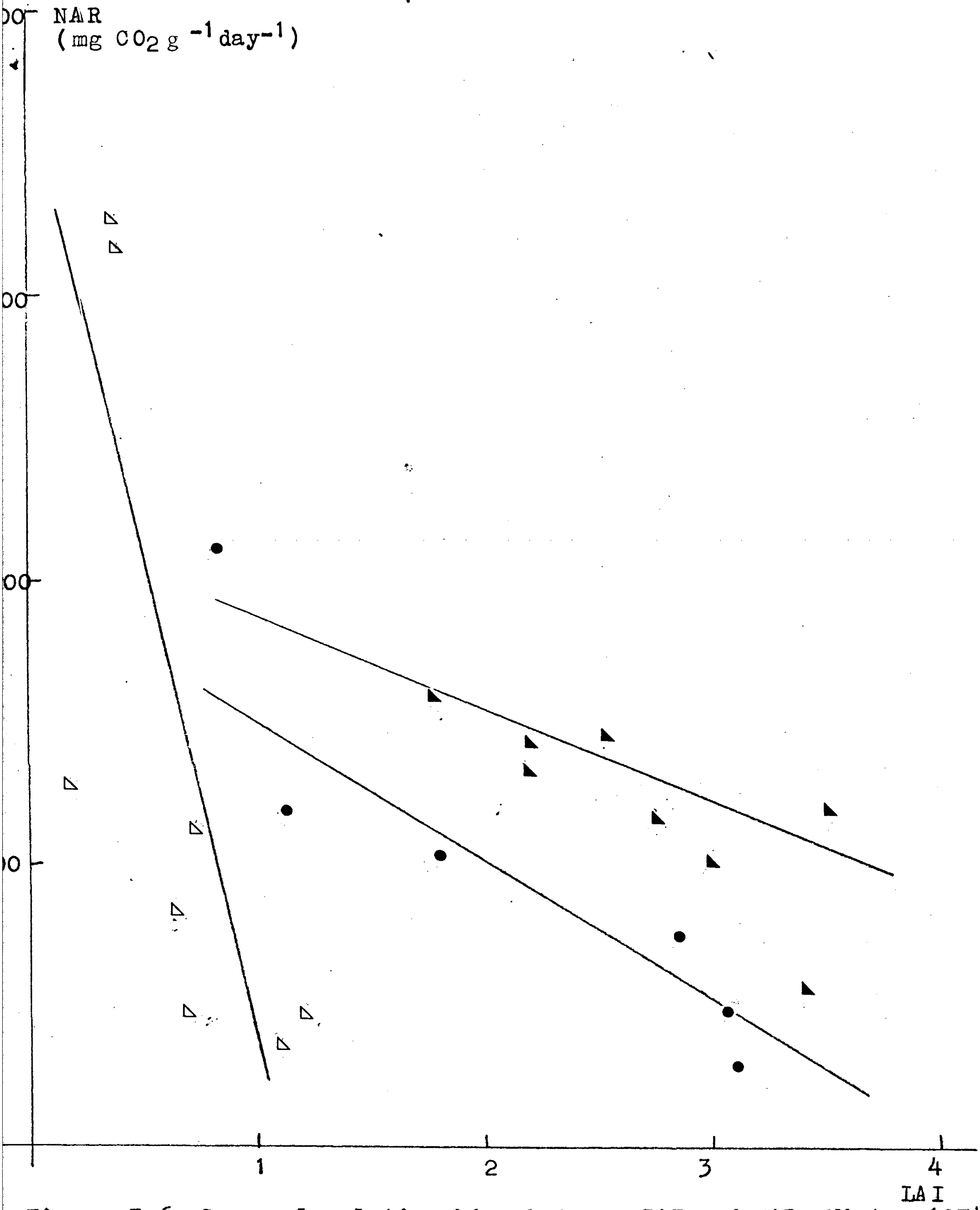


Figure 3.6: Seasonal relationships between LAI and NAR. Winter 1974 (●——●), Spring 1974(◣—◣), and Autumn-Winter 1975 (◺—◺).

regression equation was calculated (Figure 3.7):

$$LAI = 0.0016*W - 0.51 \quad (r^2 = 0.83)$$

where W = weight of green herbage (kg DM ha^{-1})

The absence of any significant curvilinear component in the regression was unexpected, since it seemed more likely that LAI would increase at a decreasing rate with increasing herbage weight. The possibility cannot be excluded that this response was a result of the difficulty experienced in measuring the area of clover leaves.

Relationship between soil temperature and soil respiration

Daily rates of carbon dioxide released from the soil under the pasture were calculated from the 2 hr measurements made on the defoliated sod at the end of each run. Table 3.3 shows that the release of carbon dioxide from the soil varied seasonally from 9.6 g m^{-2} day^{-1} in July 1974 to 42.5 g m^{-2} day^{-1} in April 1975. Figure 3.8 shows that these variations followed very closely the seasonal variations in mean soil temperature measured at 4 cm depth in the sod. The following regression equations describe the respiration responses for the July-September, October-December and March-June periods respectively:

$$SOILRES = 17.72 + 3.226\ t\ e^{0.0074\ t^2} \quad (r^2 = 0.93) \qquad (6)$$

$$SOILRES = 63.93 + 0.0949\ t\ e^{0.011\ t^2} \quad (r^2 = 0.95) \qquad (7)$$

$$SOILRES = 85.81 + 0.0085\ t\ e^{0.01\ t^2} \quad (r^2 = 0.85) \qquad (8)$$

where SOILRES = carbon dioxide released by the soil (mg h^{-1})

t = temperature of sod (^{o}C)

The flush of carbon dioxide in early spring, represented in Figure 3.8 by those points on the July-September curve corresponding to 12 and 14^{o}C, suggests that, when temperatures began to rise, fresh substrate material became available to a rapidly growing bacterial population. This material could be provided by roots, stubble and debris added

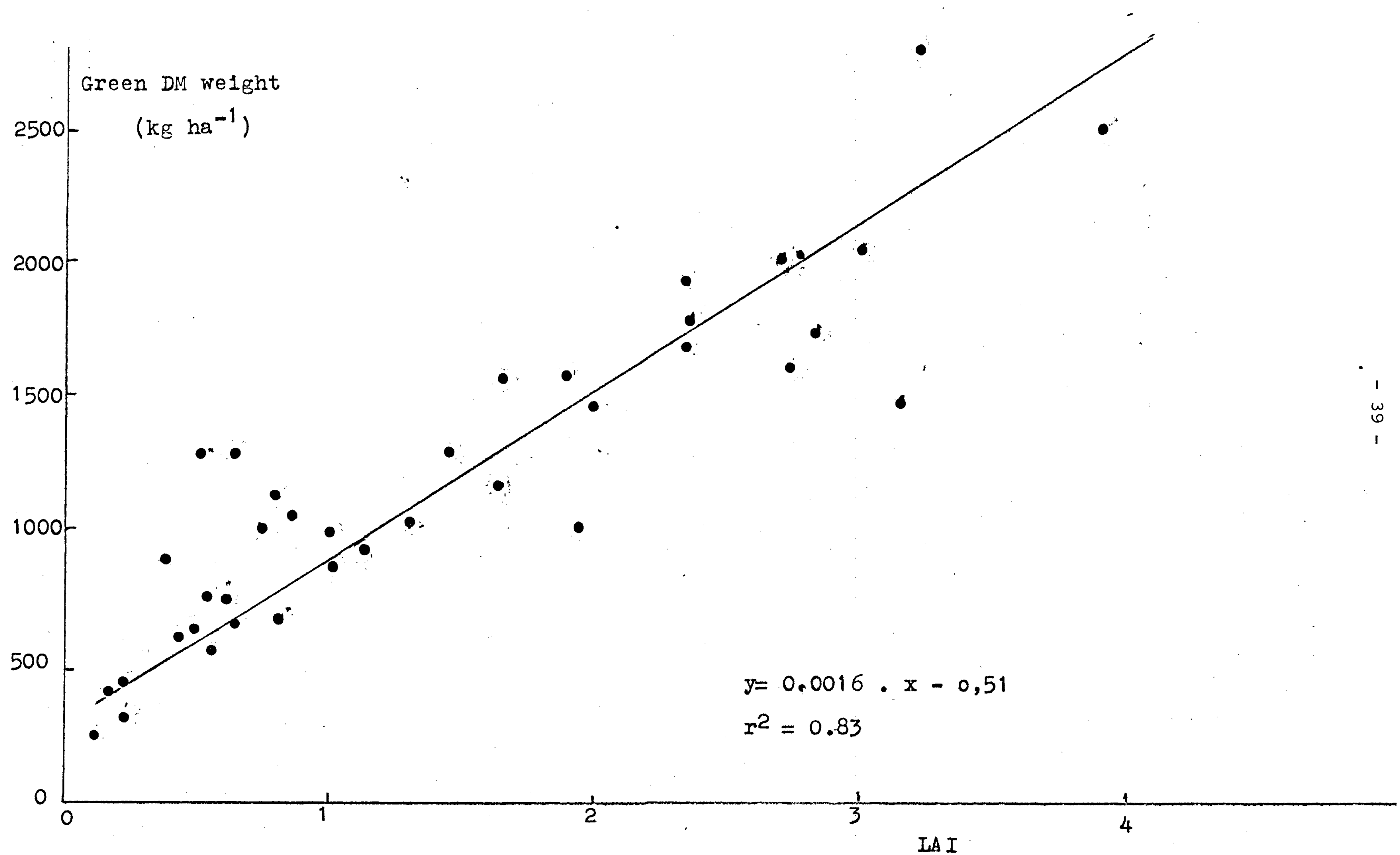


Figure 3.7: Relationship between LAI and green organic dry matter weight for two Phalaris tuberosa- Trifolium subterraneum pastures

TABLE 3.3: The effect of time of year and temperature on the carbon dioxide evolution from a soil under a *Phalaris tuberosa-Trifolium subterraneum* pasture

Sampling period	Replicate	Flux of carbon dioxide (g m^{-2} day^{-1}) 7 sheep ha^{-1}	Soil Temperature (^{o}C)	30 sheep ha^{-1}	Soil Temperature (^{o}C)
3-10 July	1	11.15	7.0	9.62	7.5
	2	19.68	10.0	10.97	9.0
31 July-1 August	1	15.24	10.5	10.45	6.5
	2				
20-21 August	1	12.79	9.5	13.09	9.5
	2				
12-18 September	1	40.73	14.0	19.78	11.0
	2	19.92	10.0	25.32	11.5
8-15 October	1	15.07	9.0	9.82	8.0
	2	12.62	9.5	14.90	9.5
4-11 November	1	40.07	20.2	28.22	13.8
	2			16.36	17.0
2-7 December	1	21.64	17.5	14.75	15.5
	2	27.43	19.0	30.29	18.7
9-10 January	1	37.54	25.0	30.31	20.5
	2				
6-14 March	1	33.36	24.8	22.15	22.5
	2	17.30	18.8	16.52	18.0
8-18 April	1	19.52	20.5	18.04	19.1
	2	45.50	25.2	16.84	18.1
7-16 May	1	21.16	15.9	21.75	16.0
	2	11.94	14.8	23.47	15.6
10-20 June	1	13.18	7.5	15.69	10.0
	2	13.47	9.0	15.71	9.0

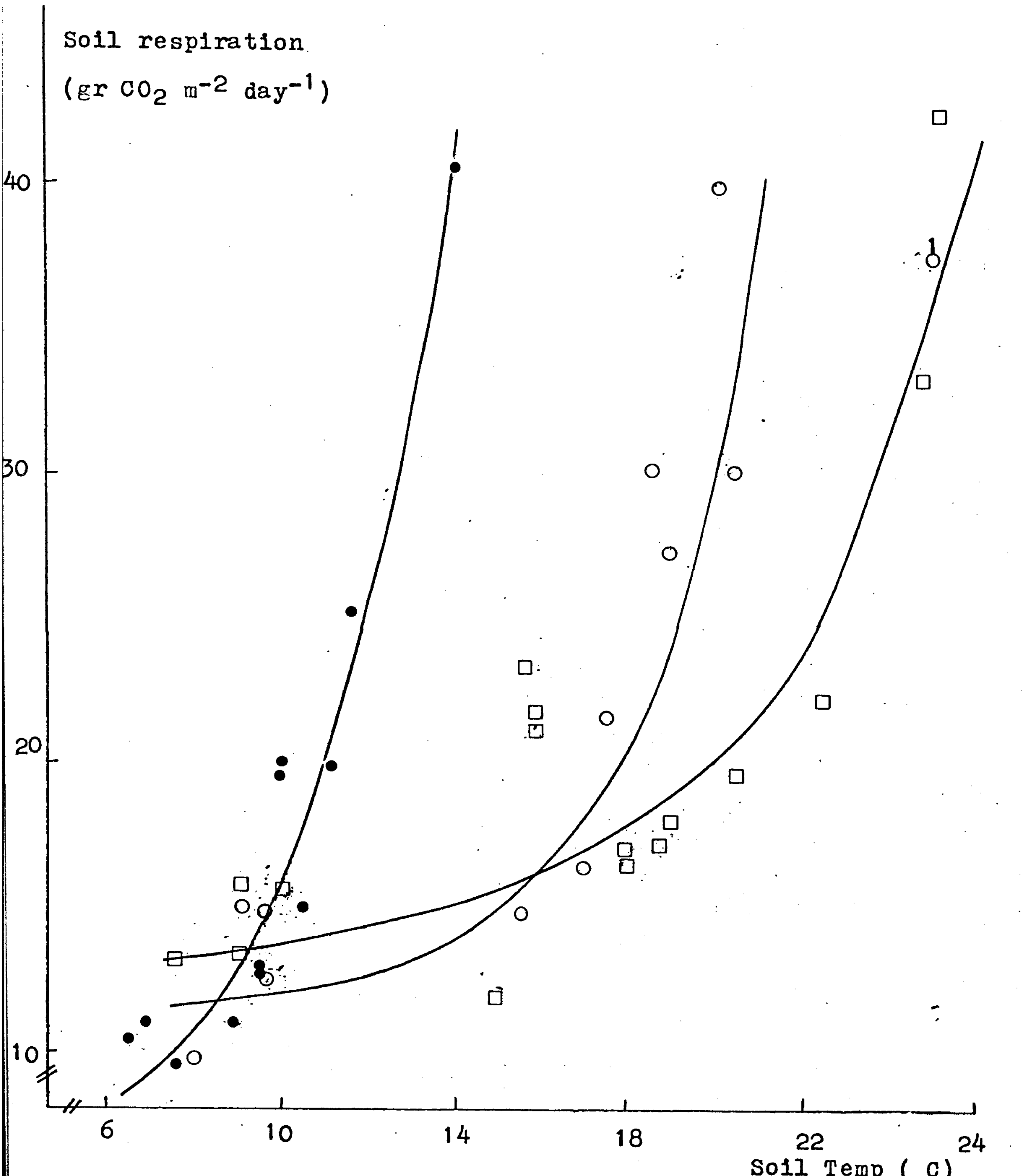


Figure 3.8: Seasonal variation in the respiration rate of a soil under a Phalaris tuberosa-Trifolium repens pasture, in relation to soil temperature (periods: July-September ●—●, October-December ○—○, March-June □—□). Point 1 (○) corresponds to a sample taken in early January when soil moisture was low which may have reduced the rate of soil respiration. This phenomenon was also observed by Monteith et al (1965).

during the previous autumn and preserved during the period of low winter temperatures. As this substrate became exhausted, the rate of decomposition would decrease and the biomass may then have remained in equilibrium from October to December, with soil respiration values falling on the same curve. In the following autumn, a further decline in slope (equation (8)) may have followed the exhaustion of nutrients available to zymogenous bacteria (Monteith *et al.* 1965).

The hourly variation in soil respiration occurring during the 24 hr measurements of photosynthesis and respiration, was estimated for the different seasons from equations (6), (7) and (8). The resulting values of SOILRES were then used in equation (2) above.

DISCUSSION

Net primary production (NPP) of pasture ecosystems may be increased by the use of superior plant genotypes, irrigation or fertilizers. An increase in stocking rate may also influence NPP (Vickery 1972) and, additionally, it may divert a greater proportion of the NPP towards domestic animal production and away from competing consumers and decomposers (Hutchinson 1971).

The data summarized in Table 3.4 show that NPP, here expressed as total carbon dioxide assimilation by the tops for each season, was 30.8 *per cent* greater at the higher stocking rate. Comparing grazed and ungrazed areas of a desert community, Pearson (1965) found a 12 *per cent* greater primary production on the grazed area. From estimates of NPP made by Hutchinson (1971) it can be argued that a heavier stocking density is most likely to result in a greater NPP of shoots.

It must be borne in mind that the measurements of carbon dioxide assimilation were made with non-limiting water supply. This means that the results represent the potential NPP of the pasture under different grazing regimes and are therefore likely to overestimate actual production under field moisture conditions.

TABLE 3.4: Total quantity of carbon dioxide assimilated by the tops of a *Phalaris tuberosa-Trifolium subterraneum* pasture in winter and spring 1974 and in autumn 1975 (g CO_2 m^{-2})

Season	Stocking rate (sheep ha^{-1}) 7	30
Winter	804	971
Spring-early Summer	2390	3063
Autumn	804	1196
Total for 44 weeks	3998	5230

The NPP of a plant community (uncorrected for root respiration) may be estimated from the product of carbon dioxide uptake per unit dry weight of assimilating tissue (NAR) and the dry weight of assimilating plant material (DMWEIT).

i.e. NPP = NAR*DMWEIT (9)

Factors such as leaf area index, botanical composition of the sward, respiration demands of the root biomass and grazing pressure will influence in different ways the magnitude of the components of this calculation. Seasonal variation in climatic inputs, e.g. incident energy, may also affect the nature of the relationship between certain components such as LAI and NAR (Brown and Blaser 1968). Hence, maximizing NPP requires an understanding of the numerous interactions operating in a grazing system and the adequate management of these factors in order to maintain an optimum combination of input components throughout the year.

Net primary production and the factors involved in the seasonal and between-treatment variation in its components

A number of studies on pasture growth have demonstrated that LAI plays an important role in determining the rate of dry matter production of the sward (Black 1955, 1963, 1964, Davidson and Donald 1958, Brown and Blaser 1968). The general conclusions from this work are that (i) growth rate increases with increasing LAI until most of the incident light has been intercepted; (ii) optimum LAI occurs when nearly all the available light has been intercepted and the ratio of photosynthesis to respiration is maximal; and (iii) an increase in LAI beyond the optimum shades the lower leaves etc. so heavily that, for these fractions, respiration exceeds photosynthesis, with a resultant drop in growth rate.

In view of the linear relationship between LAI and green herbage yield (Figure 3.7), equation (9) would suggest that NPP should be directly proportional to increases in LAI. The non-proportionality of this relationship in fact, is accounted for by the linear decline of NAR as LAI increases (Figure 3.6). This finding agrees with the results reported by Watson (1958) from studies of crop growth with *Beta vulgaris* and *Brassica oleracea*. It follows that NPP will reach a maximum at an LAI value one-half as large as the value at which NAR drops to zero.

In addition to this, the optimum LAI, i.e. the LAI at which growth rate is maximized, is dependent on plant factors such as species, inclination of leaves and canopy architecture, and meteorological factors controlling incoming radiant energy and its angle of incidence. Thus Black (1964) reported that the optimum LAI for subterranean clover varied from 4 to 7 in response to variations of incident energy from 100 to 700 cal cm^{-2} day^{-1}.

The results from the present experiment show seasonal variations in carbon dioxide assimilation as well as a differential pasture response to stocking rate.

(a) Seasonal variations

The continuous increase in carbon dioxide assimilation which occurred between late winter and early summer was associated with the increasing amount of solar radiation and more favourable temperature. In the last two winter months, the increase in the rate of carbon dioxide assimilation must have been accounted for by the increase in NAR (Figure 3.1) since the weight of green dry matter remained almost unchanged during this period (Figure 3.3). The reduction in LAI in winter (Figure 3.5) (probably caused by consumption being greater than growth) in contrast with a continuous increase in solar radiation would result in an increasing NAR because of the increasing energy available per unit leaf area for photosynthesis.

The change in the slope of the NAR curve in early spring (12-18 September sampling) suggests that after this point, carbon dioxide assimilation became dependent on the rate of increase of green dry matter. At this point, the latter reached a level sufficiently high to compensate for the decline in NAR occurring thereafter, with the result that a high rate of carbon dioxide assimilation was maintained through the rest of the spring.

In the following autumn, low initial values for LAI (Figure 3.5) were associated with high values of NAR. The subsequent increase in LAI led to a steep decline in NAR and a resultant decrease in the rate of carbon dioxide assimilation. The generally low values at this time of the year would also be related to the reduced weight of green herbage in both swards (Figure 3.3).

(b) Between-treatment variation

The 31 *per cent* greater NPP (or carbon dioxide assimilation) shown by the heavily grazed pasture (Table 3.4) is the result of differing seasonal combinations of the components of equation (9) in each treatment. The average LAI values during the winter months were 3.00 and 1.24 for the 7 and 30 sheep ha^{-1} respectively. In view of the relationship depicted in Figure 3.6, it follows that heavy grazing resulted in higher values of NAR than did lenient grazing. The difference in carbon dioxide assimilation that might otherwise have been expected from differing amounts of green herbage (Figure 3.3), may have been offset by the differences in NAR (Figure 3.1).

The higher rate of carbon dioxide assimilation observed under heavy grazing in the spring-early summer period is the result of a slightly higher mean NAR, 132 compared with 113 mg CO_2 g^{-1} day^{-1} for heavy and lenient grazing respectively (Table 3.1), and a more rapid rate of increase of photosynthetic material in early spring (Figure 3.3). However, the reverse situation applies to this period with respect to the relationship between LAI and NAR since, despite higher values of LAI on the heavily grazed pasture (Figure 3.5), they showed a greater NAR. As the value of NAR is the difference between the rates of photosynthesis and respiration it can be expected that an increase in respiratory demand will reduce NAR. Measurements of root respiration have indicated that ca. 1.95 mg CO_2 g^{-1} root dry matter is necessary for root growth (Newton 1923, Monteith 1965). The average root biomass in spring at 7 sheep ha^{-1} was 2677 kg ha^{-1} greater than at the higher rate, which means an increased respiratory demand of 5.22 kg CO_2 ha^{-1} and this may well have caused the observed reduction in NAR, Root respiration may have been a factor causing differences in NAR in all seasons since differences in root biomass of a similar magnitude occurred throughout most of the year (Figure 3.4).

After cessation of growth in summer, both swards had low values of LAI, from which high values of NAR could have been expected in autumn, once temperature and soil moisture conditions became more favourable. The heavily grazed pasture showed its highest NAR at the beginning of autumn and consequently its rate of carbon dioxide assimilation was greater than that of the leniently grazed pasture, despite the lower quantity of green herbage present. In contrast, lenient grazing resulted in a low NAR for this period, probably due to shading of the green leaves at the base of the canopy by the bulk of standing dead material remaining from summer. The low soil moisture during the summer prevented the decomposition of dead herbage accumulated at the end of spring.

From the above discussion, it is concluded that the heavily grazed sward was able to attain higher levels of above ground NPP, and this was partly by means of a higher NAR, particularly in autumn and winter.

The potential for net primary production and its utilization in different grazing systems

In any environment, the ultimate limit to production of forage is set by the available energy input. However, in practice, yields are also limited by three other important environmental factors, temperature, water and nutrients. Temperature is an uncontrollable factor in grazing systems, whereas the potential for controlling the other two factors depends mainly on the profitability of the practice and the availability of physical resources.

Estimates of potential production from temperate grasslands (Loomis and Williams 1963, Black 1964, Cooper 1970, Hutchinson 1971, Cocks 1974) are at least twice the actual production achieved under agricultural conditions, either from undefoliated (Donald 1951, Lawson and Rossiter 1958, Black 1957) or defoliated swards (Davidson and Donald 1958, Black 1964, Carter and Day 1970, Parrot and Donald 1970).

As a way of approaching potential production when the control of no other environmental factors can be improved, there still exists the possibility of using adequate defoliation regimes in order to make best use of the light environment. The estimates of potential production presented in Table 3.5 may be compared with the results reported by Donald (1951) on the maximum yields of ungrazed swards of subterranean clover in the Canberra area under conditions of ample water and nutrient supply. During a similar 44 week period in which Donald recorded on above ground NPP of 9000 kg DM ha^{-1}, the NPP measured in this experiment, after allowing a 10 *per cent* reduction for root respiration and assuming that half of the whole plant NPP occurs below ground, was 8100 kg DM ha^{-1} in the pasture grazed at 30 sheep ha^{-1}. The agreement is good, considering the difference in the experimental techniques used in the two estimates.

However, little would be gained by increasing NPP if this were not paralleled by efficient utilization of the higher level of production. This will depend on the development of management systems in which the optimum frequency and intensity of cutting or grazing for production of the sward are balanced against the seasonal requirements of the ruminant.

Although, in the present experiment, the intake by grazing animals was not measured, the data on NPP (Table 3.4) and on standing dead material (Table 3.2) gives some evidence in support of increased feed utilization. At 30 sheep ha^{-1}, 5545 kg DM ha^{-1} (or 2357 kcal m^{-2}) more

TABLE 3.5: Seasonal variations in growth rate and total plant production of a *Phalaris tuberosa-Trifolium subterraneum* pasture under grazing, for the year July 1974-June 1975 in the Canberra region.

Sampling period	7 sheep ha^{-1}		30 sheep ha^{-1}	
	Growth rate ($kg\ ha^{-1}\ day^{-1}$)	Accumulated growth ($kg\ ha^{-1}$)	Growth rate ($kg\ ha^{-1}\ day^{-1}$)	Accumulated growth ($kg\ ha^{-1}$)
3-10 July 1974	37.1	1032	44.1	1226
31 July-1 August	63.4	2795	63.9	3003
20-21 August	67.6	4675	41.2	4149
12-18 September	108.6	7695	98.9	6899
8-15 October	110.2	10760	171.8	11677
4-11 November	147.3	14856	140.5	15585
2-7 December	116.7	18102	184.6	20718
6-14 March 1975	103.9	20991	135.8	24495
8-18 April	55.6	22537	118.9	27802
7-16 May	60.2	24211	67.7	29684
10-20 June	44.3	25443	46.9	30988

Notes:
(1) Each growth rate figure is taken to apply for a 28-day period, 14 days before and 14 days after the date of measurement.
(2) From approximately 1 January to 28 February no growth occurred, so total herbage production is calculated over 10 months.
(3) The growth rates were calculated from the estimates of whole plant NPP, using the factors described on p. 25. As mentioned earlier, these estimates are uncorrected for root respiration.

was produced during the year than at the lower stocking rate. Furthermore, 2256 kg DM ha^{-1} (or 959 kcal m^{-2}) less was lost by senescence and decomposition, suggesting that over the whole period about 3300 kcal m^{-2} more passed through the animal biomass. This could be expected to result in higher levels of animal production and Hutchinson (1971) found that increasing the stocking rate from 10 to 20 sheep ha^{-1} caused the yield of clean wool to rise from 33 to 61 kg ha^{-1} $year^{-1}$.

As only two stocking rates were examined, there is no suggestion that 30 sheep ha^{-1} was the optimum rate for these pastures. In any case the optimum rate is likely to vary from year to year and it seems inevitable that grazing systems must be examined over a wide range of stocking rates for a number of years in order to establish which grazing regimes provide the conditions for the most efficient level of productivity.

CHAPTER 4:

A STUDY OF THE EFFECTS OF GRAZING MANAGEMENT ON THE GRAIN YIELD OF WINTER CEREALS

INTRODUCTION

The first relevant question to ask is: why is it important to understand the effect of defoliation by grazing on the subsequent grain yield of winter cereals? These crops, when sown early enough, have the capacity to produce leafy material at a time when pasture production is slow. Furthermore, many winter cereals are well adapted to grazing during their vegetative stage of growth. However, the reported effects of grazing on subsequent grain yield have varied widely (see reviews by Holliday (1956) and Dann (1972)) and it is probable that this variation arises from interactions between grazing management and morphological or physiological characteristics of the species or varieties concerned.

In the absence of other limitations, plant growth is a function of the amount of leaf tissue exposed to sunlight (Watson 1952; Donald and Black 1958). Hence, it is important in assessing grazing management policies for winter cereals that defoliation be defined in terms of the green material remaining. However, most reported experiments have centred attention on the response of the crop to date of defoliation, the length of the grazing period or the height of defoliation. Considering the variation in rate of development and growth habit between different environments or crop varieties, these criteria are likely to be inadequate indicators of the growth potential of the crop at the end of grazing.

The adaptation of winter cereals to grazing depends on morphological and physiological features and variations in these probably cause some of the differential responses to defoliation observed between crop species and varieties. Grasses have either culmed or culmless vegetative shoots (Hyder 1972). In the former type, the shoot apex is elevated and the extent and time of elevation affects the leaf replacement potential as well as the resistance to grazing. In grasses with culmless shoots, the basal position of the apical meristems and leaf primordia protects the sources of further leaf expansion and leaf replacement after defoliation.

In the early stages of development, winter cereals may have a form of growth similar to that of culmless vegetative shoots, since a number of leaves may emerge and reach maturity before the initiation of internode elongation. Once internode elongation begins, the shoot apex and culm leaves are elevated. Shoot apices thus elevated soon become susceptible to removal by grazing. In this event, leaf replacement and additional growth then require the initiation of activity in axillary buds and the appearance of new shoots. Subsequently, differentiation of the shoot apex to reproductive status further increases the vulnerability of the plant to defoliation. Grazing at this stage may have a direct effect on grain yield as potential ears may be removed. The observed variation between winter cereals in the pattern of development and movement of the shoot apex (Washko 1947) increases the importance of the decision on the species or variety to be used as a dual-purpose crop.

Returning to the original question, the main practical object of including winter cereals in a grazing system is to provide a source of feed at a time of year when the growth of pasture plants is slower, probably because of a lower maximum relative growth rate (J.L. Davidson, personal communication). By doing this, the grazier may offset the reduction in grazing area which results from planting the crop and, at the same time, achieve a valuable diversification of production to meet typically variable market conditions. However profitability will depend largely on the grain yield and the grazing of winter cereals must be carefully managed to avoid reducing this. The optimum management policy for any particular grazing system is unlikely to be revealed by experimentation but systems analysis and simulation offer a practicable alternative, as described in Chapter 2. What experimentation must provide, however, are quantitative data on the relationship between defoliation and grain yield that can be used in such a system. The experiment described in this Chapter was designed to measure the grain yield from a number of cereal crops after these had been grazed for different periods in winter to leave different weights of green dry matter.

MATERIALS AND METHODS

Design

The experiment was conducted in 1974 at the CSIRO Ginninderra Experiment Station situated near Canberra. Four winter cereals were grown in a predominantly grey podzol soil with heavy texture. The varieties were selected on the basis of commercial use and/or recommended use in the area as forage and grain crops; they comprised: Coolabah oats, Resibee barley, M1313 winter wheat, WW31 (Egret) spring wheat.

The experimental treatments were: 20, 40, 60 and 80 days of grazing at two intensities - high and low. Grazing intensity was defined in terms of green herbage remaining after grazing. The levels chosen were 500 kg ha^{-1} and 1000 kg ha^{-1} for the high and low treatments respectively. These treatments were compared in a

4 x 4 x 2 randomized factorial design with two replications. Within each plot, subplots measuring 2 m x 30 m were allotted at random to the four crops. Four ungrazed plots were included as controls.

Establishment and Management

All crops were sown on March 20 at a rate of 90 kg ha^{-1}, together with 250 kg ha^{-1} of single superphosphate. Before the start of grazing all plots were top-dressed with 180 kg ha^{-1} of ammonium nitrate.

Grazing by Merino wethers weighing 28.5 ± 1.52 kg commenced on June 14 on all plots, when the plants were sufficiently rooted as to withstand heavy grazing. Rotational grazing was used throughout the experiment based on a 5-day grazing, 10-day spelling system. Each grazing was imposed on all plots at the same time and for the same length of time. Thus, grazing management was standardized to make sure that all crops were grazed at the same chronological age. Before the commencement of each 5-day defoliation period, grazing intensity was adjusted on the basis of measurements of the green material present and estimates of animal intake. This was intended to avoid grazing the crops below the level of remaining herbage set for the treatment concerned.

Measurements

The weight of green dry matter present on each plot was measured at the start of grazing, before and after each grazing period and at 25-day intervals from the end of grazing until flowering by means of an electronic capacitance pasture meter (Jones and Haydock 1970). A regression of meter reading against weight of green dry matter was established at each sampling by cutting one 60 x 60 cm quadrat of known meter reading from each of the thirty two treatments. Four random meter readings were taken on each subplot and the mean reading was used for the yield estimates. The herbage within the quadrats was cut to ground level since the instrument used has been reported to measure all the vegetation above ground level (Alcock and Lovett 1967).

Eight additional grab samples, each consisting of 30 cm length of row in each of rows 2 to 9 (outside rows discarded), were taken per subplot to assess the proportion of living and dead material. These samples were sorted into green and dead fractions and dried in an oven. The proportions of green and dead dry matter were then calculated and applied to the yields measured from the calibration quadrats to compute the regression equation of weight of green materials on meter reading.

At flowering, yields of total and green dry matter were measured by means of the grab-sample method because the use of the capacitance meter at this stage of growth would have underestimated yields (Lazenby and Lovett 1975). In addition, counts were made of the following yield components: number of live and dead plants, number of live, dead and truncated tillers and number of ears.

At maturity, the entire plots were harvested to measure final grain yield. Before harvesting, 20 ears were removed from each plot to estimate number of grain per ear and mean grain weight.

Climatic Conditions

The long term meteorological data for the Canberra area (Table 4.1) shows that the months June, July and August are the only period when, on average, a positive water balance can be expected in this

TABLE 4.1: Climatic data for Canberra (lat. 35°10'; long. 148°48'; alt. 578.5 m)

Attribute	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Long term means:													
Max. temp (°C)*	27.5	26.6	24.3	19.6	14.9	12.0	11.1	12.6	15.8	19.0	22.2	26.0	19.3
Min. temp (°C)*	12.9	12.6	10.4	6.5	2.8	0.8	-0.3	0.8	2.7	5.8	8.2	11.1	6.2
Rainfall (mm)*	61	59	51	50	51	39	38	47	50	73	64	56	639
Evap. (mm)**	246	191	158	107	72	47	54	61	111	155	194	259	1656
R - E_t (mm)	-135.8	-93.8	-59.6	-24.9	+0.6	+6.1	+0.2	+4.3	-27.7	-35.5	-71.8	-151.2	-589.1
1974***													
Rainfall (mm)	95	85	53	174	45	27	73	133	79	167	64	2	997
R - E_t (mm)	-53.0	-70.2	-45.7	+131.3	+3.7	-5.2	+45.0	+93.8	+15.3	+83.0	-45.2	-214.8	-62.0
1975***													
Rainfall (mm)	47	88	67	46	24	62	89	49	110	150	15	53	800
R - E_t (mm)	-175.4	-62.4	-23.3	-19.8	-16.6	+31.9	+57.5	+7.7	+56.9	+82.1	-95.6	-105.4	-262.5

* Fairbairn Meteorological Office (A.C.T.): 36 year means (1940-1975).

** Same source. 9-year means of Pan Evaporation (Evap.). E_t = Evap. x c; c = 0.6, 0.7, 0.8 for winter, autumn and spring and summer respectively. After Penman (1948).

*** CSIRO Ginninderra Experiment Station records.

environment. Low rates of evapotranspiration make winter rainfall effective, although its potential usefulness for plant growth is limited by low average temperatures (Table 4.1). Hence, the period of active plant growth in this environment is typically restricted to autumn and spring.

This environment is also characterized by erratic rainfall and during most of the experimental period (1974) precipitation was unusually high (Table 4.1). Heavy rainfall occurred in April, bringing about an abnormal excess in the water balance. May and June were average months but, from July onwards, wet weather prevailed and a positive water balance was maintained through most of the spring.

Statistical Analysis

Data were combined in a least squares analysis of variance involving three factors: crops, intensity of grazing and length of grazing. Comparison was also made between the last two management factors with the ungrazed controls. The statistical package GENSTAT available in the CSIRO CYBER 7600 computer was used for the calculations.

RESULTS

Before the start of grazing the total dry matter yield on the oats and barley plots was similar (Figure 4.1) but this level was greater ($P<0.05$) than that on the wheat plots. The spring wheat outyielded the winter wheat at this stage but the difference was not significant.

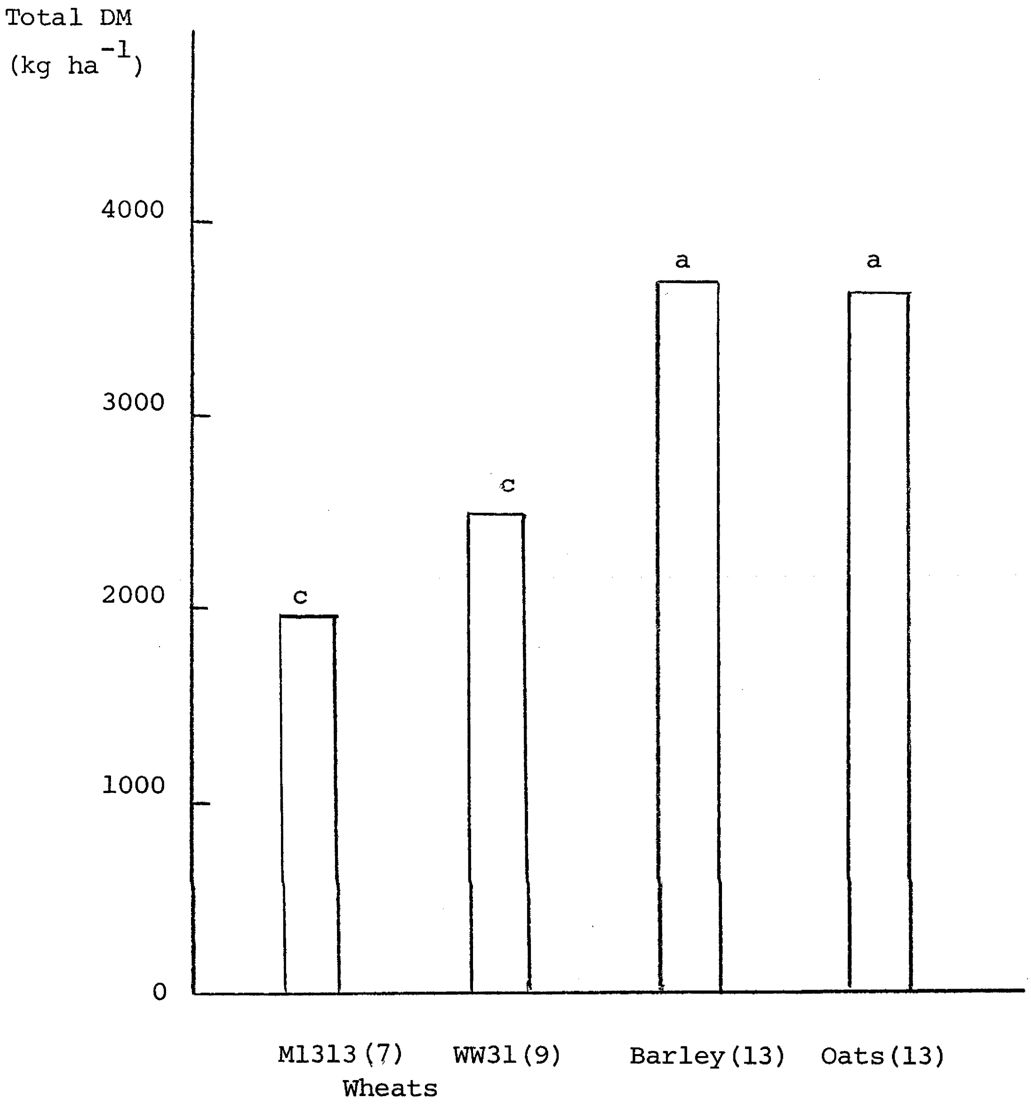


Figure 4.1: Mean dry matter yields at commencement of grazing, 14/6/74. Crops identified with the same letters do not differ at the 5% level of probability using Tukey's multiple range test, modified by Snedecor (1965, p. 251).

Green Matter Yields at the End of Grazing

At the end of grazing the weight of green material on the heavily grazed plots was 300 ± 204 kg DM ha^{-1} compared with 870 ± 409 kg DM ha^{-1} on the leniently grazed plots. An analysis of these yield measurements (Table 4.2) showed that the effect of grazing intensity was highly significant ($P<0.001$). Although the length of grazing period did not in itself affect the amount of material remaining after grazing, there appeared to be a significant interaction between length of grazing period and intensity of grazing. An examination of the data revealed two extreme outliers in the yield estimates for the 40-day grazing period (period 2), indicated by crosses in Figure 4.2. Reanalysis excluding this period showed no interaction between the variables. It was therefore concluded that the grazing intensity treatments had, as intended, established significantly different levels of green herbage dry matter at the end of grazing and that this effect was not confounded with the duration of the grazing period.

The four crops differed significantly ($P<0.001$) in availability at the end of grazing and their ranking was winter wheat, spring wheat, barley and oats (Figure 4.4). These differences must be attributed largely to the effects of selective grazing.

Green Matter Yields at Flowering

Yields of green dry matter at flowering showed very similar treatment effects to those observed at the end of grazing. Length of grazing had no significant effect (Table 4.2) although there was a consistent trend towards lower yields with longer grazing periods (Figure 4.3b). Intensity of grazing significantly reduced

TABLE 4.2: Results of the analysis of variance on weight of green material at the end of grazing and at flowering (control plots not included).

Source of variation	After grazing	At flowering	At flowering (adj.)
Length of grazing (A)			
Intensity of grazing (B)	*** (**)	** (*)	
A x B	*		
Crops (C)	*** (***)	* (*)	* (*)
A x C			
B x C			
A x B x C		(*)	

* P<0.05
** P<0.01
*** P<0.001

Values in brackets for grazing periods 1, 3 and 4

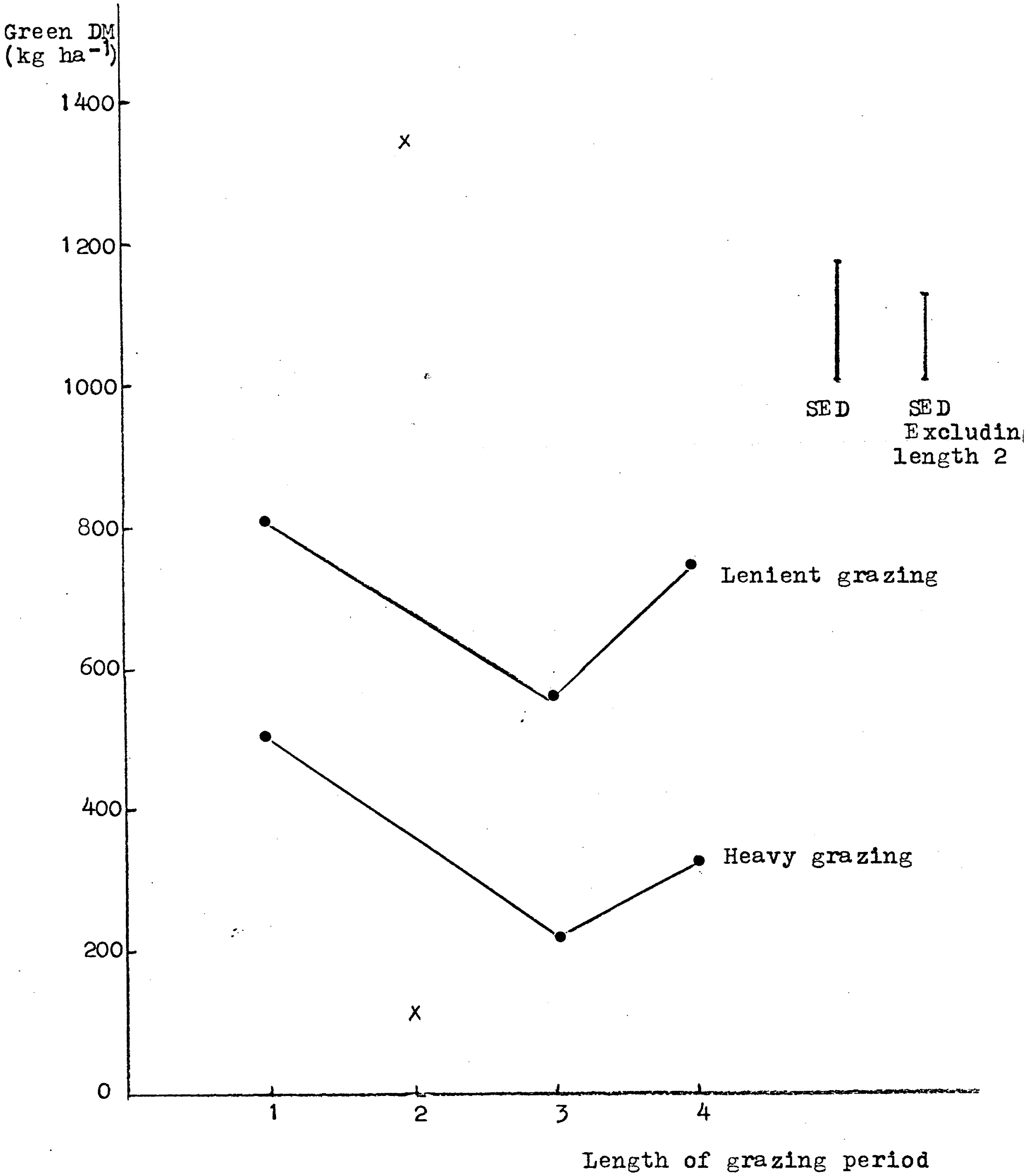
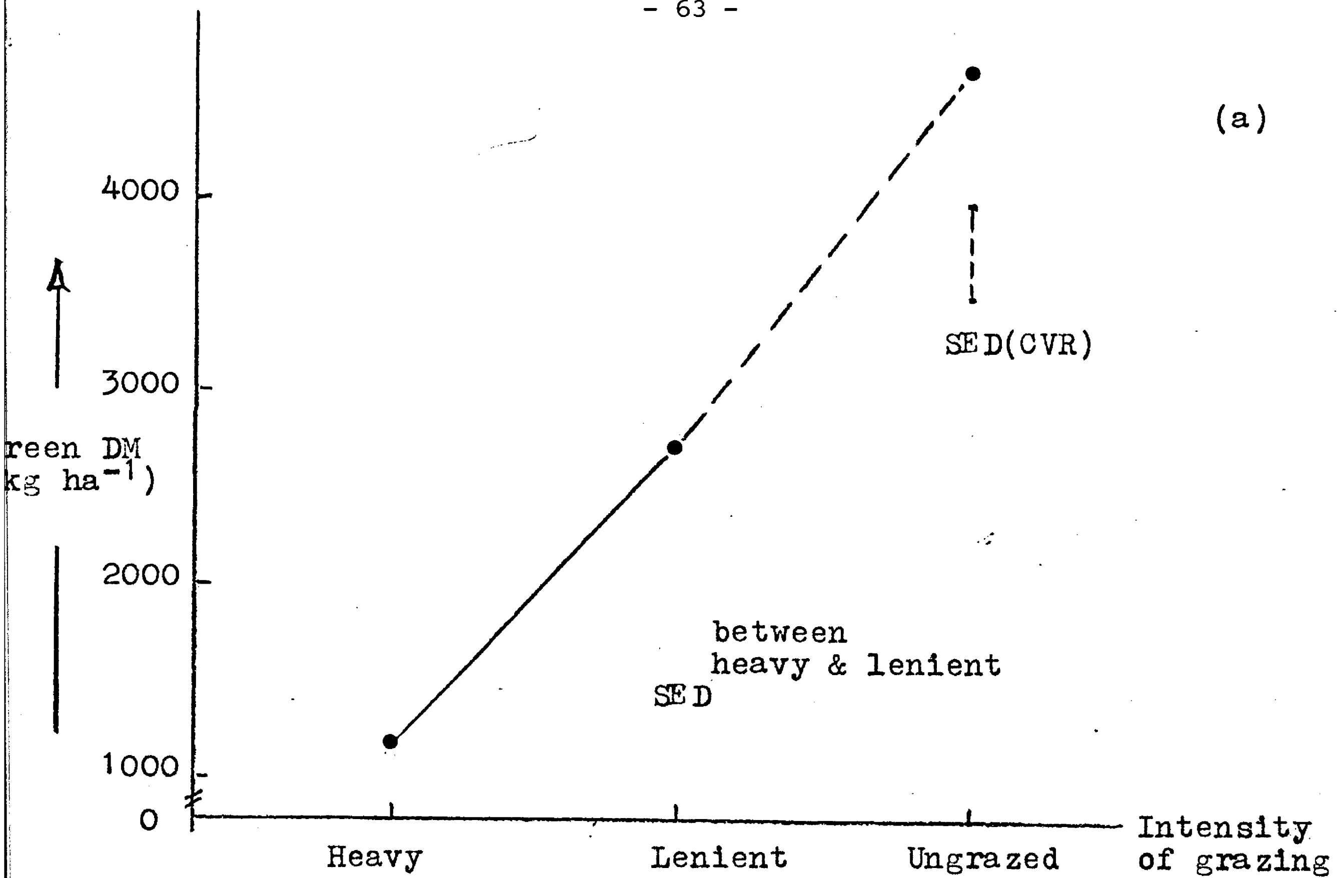


Figure 4.2: Weights of green herbage at the end of grazing



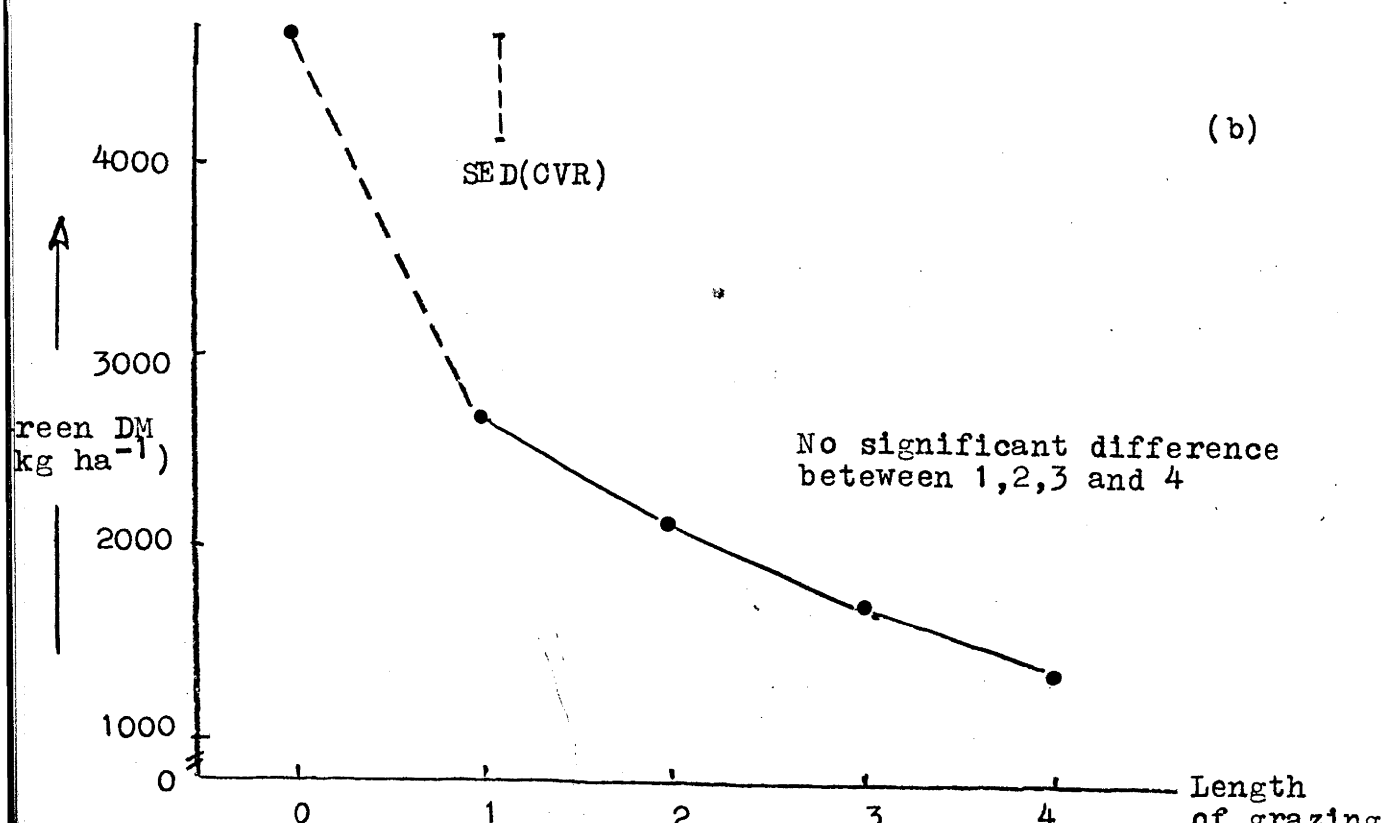


Figure 4.3: Weights of green herbage at flowering. (CVR indicates that the corresponding SED is applicable when comparing the mean of the ungrazed plots with that of the grazed ones).

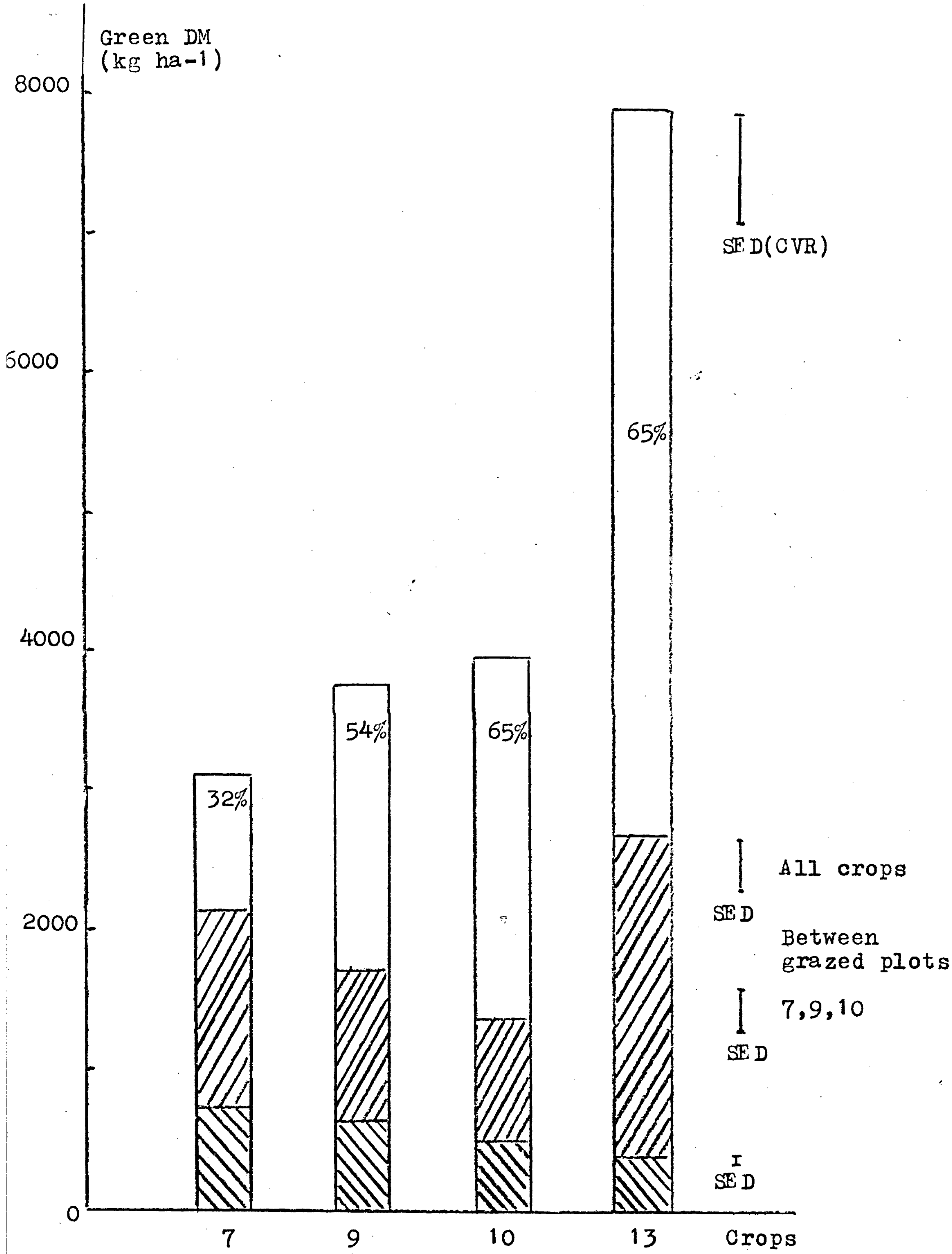


Figure 4.4: Weights of green herbage at the end of grazing (\\\\\\\\) and at flowering(/////). The total length of the bars represents yields on the ungrazed plots at flowering.

($P<0.01$) yield at both lenient and heavy grazing intensities (Figure 4.3a). Compared with the ungrazed control plots, lenient grazing reduced the dry weight of green material at flowering by 42.5 *per cent* and heavy grazing reduced it by 74.4 *per cent.*

When the yields at flowering were adjusted, using the yields measured at the end of grazing as a covariate, the analysis in col. 3 of Table 4.2 shows that the effect of grazing intensity is no longer significant. This suggests that grazing intensity did not affect the regrowth rate of the crops between the end of grazing and flowering. The only significant effect remaining after adjustment was that of crops ($P<0.01$) and the main reason for this was the superior performance of Coolabah oats (Figure 4.4). Oats produced 2800 kg DM ha^{-1} at flowering compared with 1660 kg DM ha^{-1} from the other three crops. This difference indicates a much higher regrowth rate by oats, particularly when it is considered that oats was the most selected crop during grazing and hence the one which had the least herbage remaining at the end of grazing. A comparison of the grazed crops with the ungrazed controls shows that grazing reduced the green material at flowering by 62 *per cent* for oats and barley and by 54 *per cent* and 32 *per cent* for the spring and winter wheats respectively.

Effect of Grazing on Yield Components at Flowering and Subsequent Grain Yield

Yield components at flowering showed a somewhat similar pattern of responses to those already presented for green material. Duration of grazing did not produce any significant effect (Table 4.3), although there was a consistent tendency for all yield components to decrease as grazing period lengthened (Figure 4.5). On the other hand, grazing

TABLE 4.3: Results of the analysis of variance on yield components at flowering and grain yield (including check plots)

Source of variation	Ears	Live tillers	Plants	Green DM at flowering	Grain Yield	No. grain per head	Grain weight
Control vs. rest (CVR)	*	**		**	**	***	
A				(**)	(*)		
Intensity of grazing	**	**	**	**	*	*	
B	(**)	(**)	(**)	(*)	(*)		
Length of grazing						*	
C							
Length x Intensity							
C x B							
Crops	**		*	**	***	***	***
(Means incl. checks)				(**)			

TABLE 4.3: Continued.

Crops x CVR	**	*	**	***	
	----------	----------	----------	----------	***
Crops x Length	----------	----------	----------	----------	*
			(*)		
Crops x Intensity	----------	----------	----------	----------	*

*** P<0.001
** P<0.01
* P<0.05

Values in brackets exclude results for oats

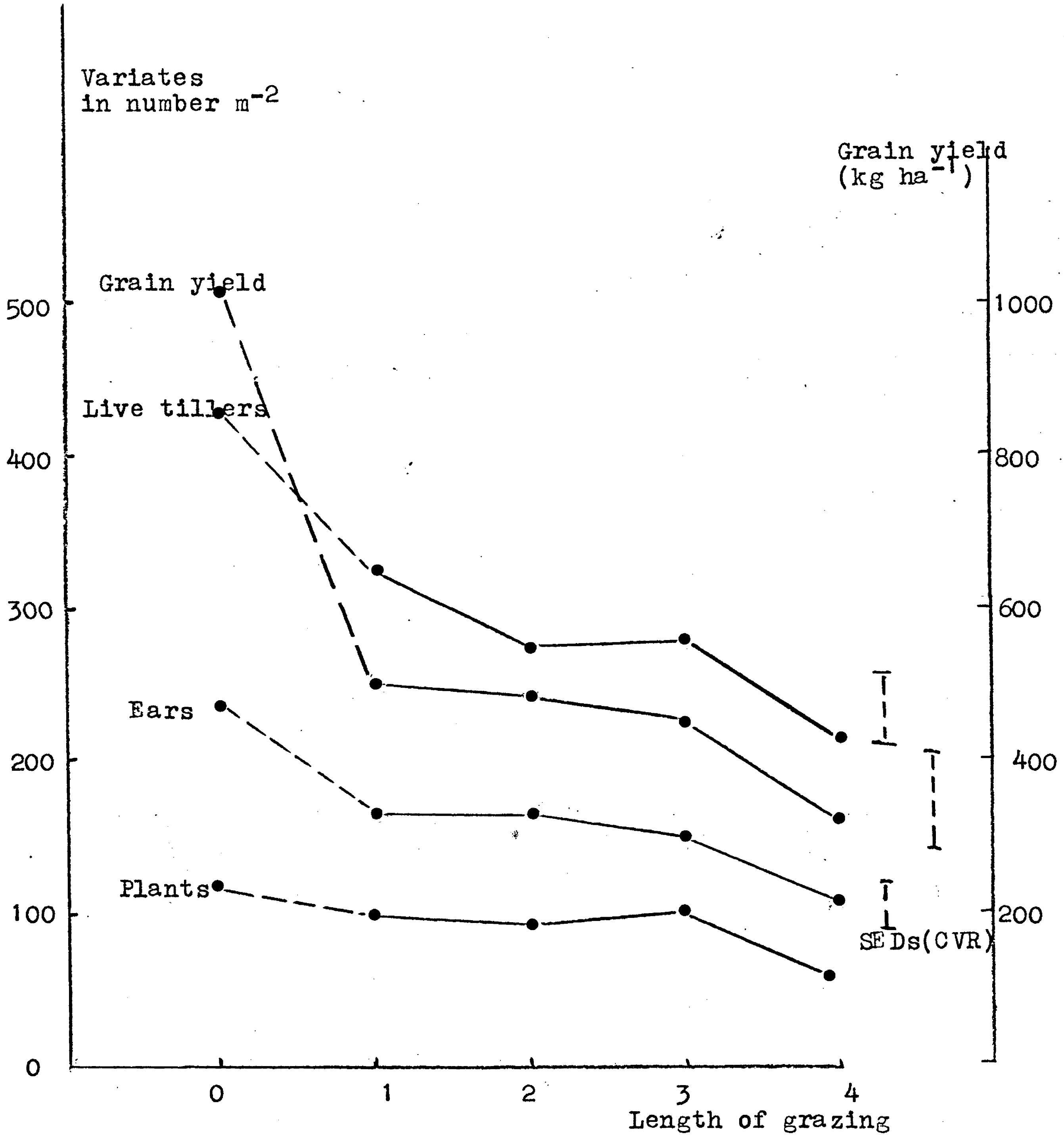


Figure 4.5: Effect of length of grazing on yield components at flowering and subsequent grain yield.

of any duration significantly reduced the number of live tillers ($P<0.01$) and ears ($P<0.05$) when compared with ungrazed plots. Analysis of the results in relation to the intensity of grazing showed that this effect was restricted to the heavy grazing treatment (Figure 4.6) which reduced the size of all the yield variables. The measurements made on the leniently grazed plots did not differ significantly from those on ungrazed plots.

A comparison of results within individual crops showed (Figure 4.7) that grazing significantly affected number of live tillers of oats and barley ($P<0.05$), as well as number of ears of oats ($P<0.01$). When the measurements on all grazed plots were compared between crops, it was found that differences in yield components were not significant.

The reproductive performance of the crops in response to grazing was assessed from the grain yield at harvest. All grazing treatments reduced grain yield ($P<0.05$) when compared with ungrazed plots and heavy grazing reduced it more than lenient grazing (Figure 4.8). However, this response applied in a varying degree to the different crops (Figure 4.9). In fact, oats, which outyielded ($P<0.01$) all of the other crops was the only one in which both levels of grazing intensity caused significant reductions ($P<0.01$) in grain yield. Of the other three crops only barley was affected significantly by grazing, producing less grain ($P<0.01$) at the heavier grazing intensity.

Measurements on the components of grain yield showed that differences between grazing treatments were caused by changes in the number of grains per head and not in mean grain weight. However, the higher grain yield of oats compared with the other crops was associated with significantly greater values ($P<0.001$) for both components

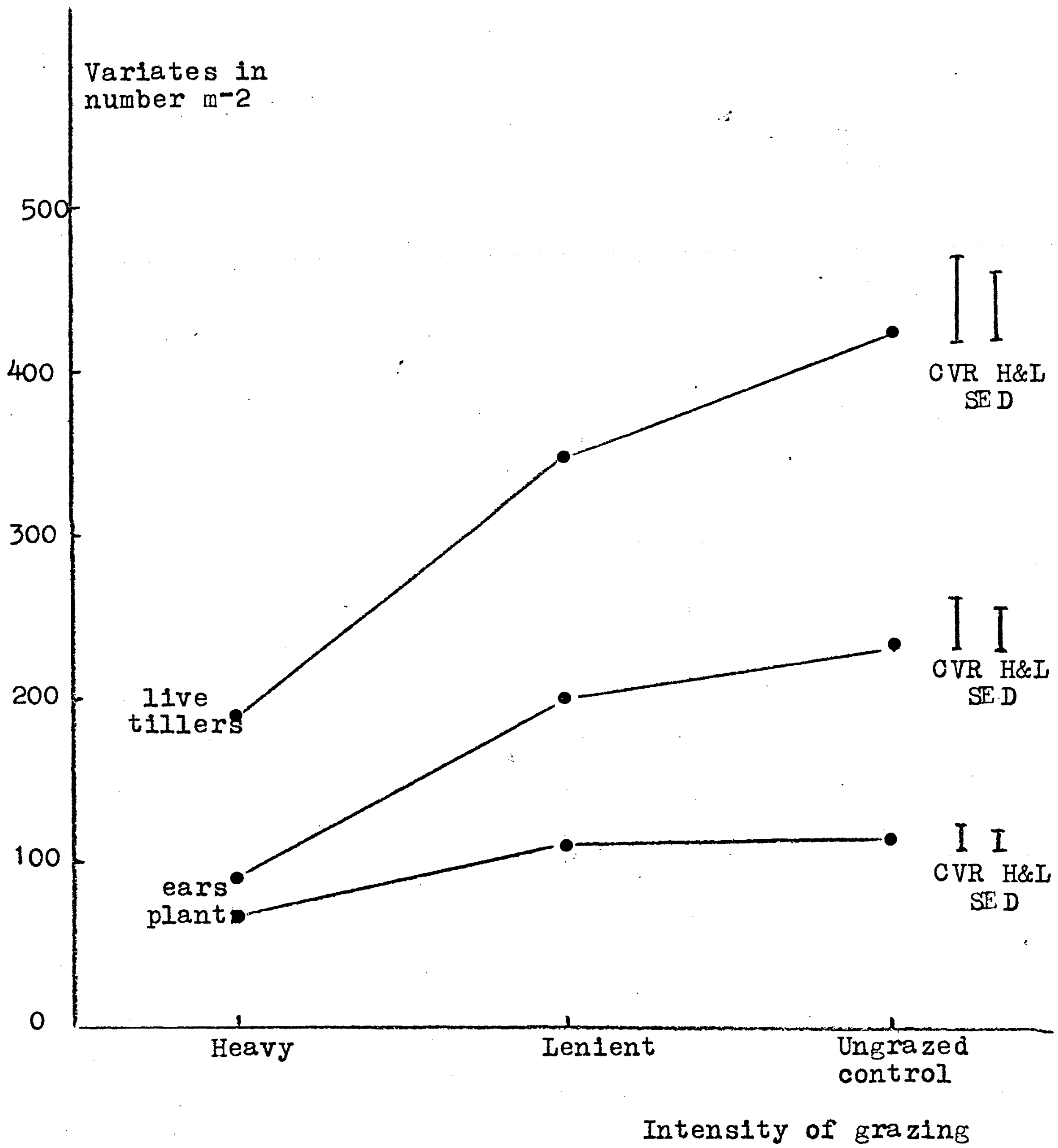


Figure 4.6: Effect of intensity of grazing on yield components at flowering(H= heavy grazing, L= lenient grazing

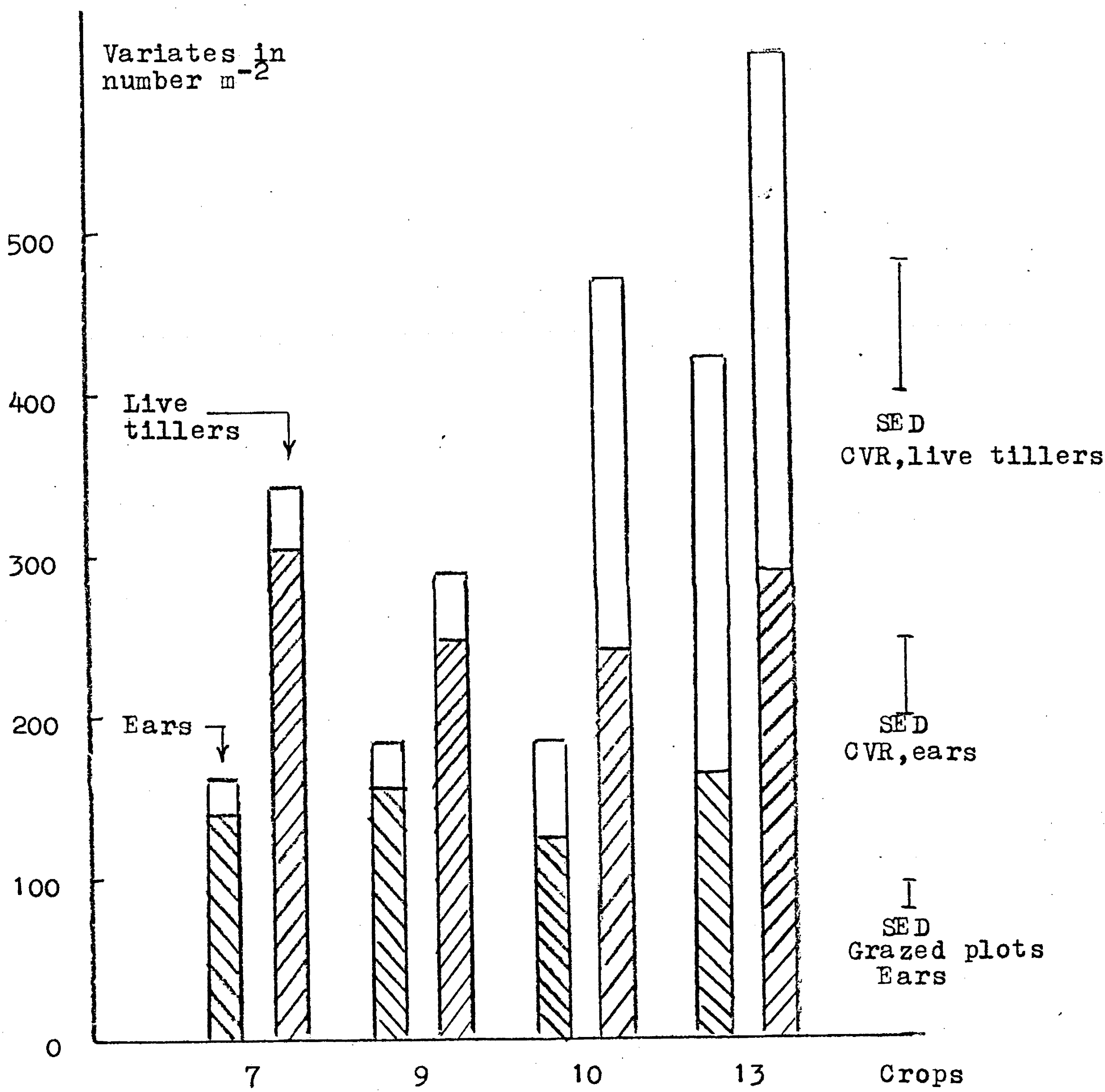


Figure 4.7: Yields components at flowering for individual crops. Means of grazed plots (shaded sections) and means of ungrazed controls (total length of bars).

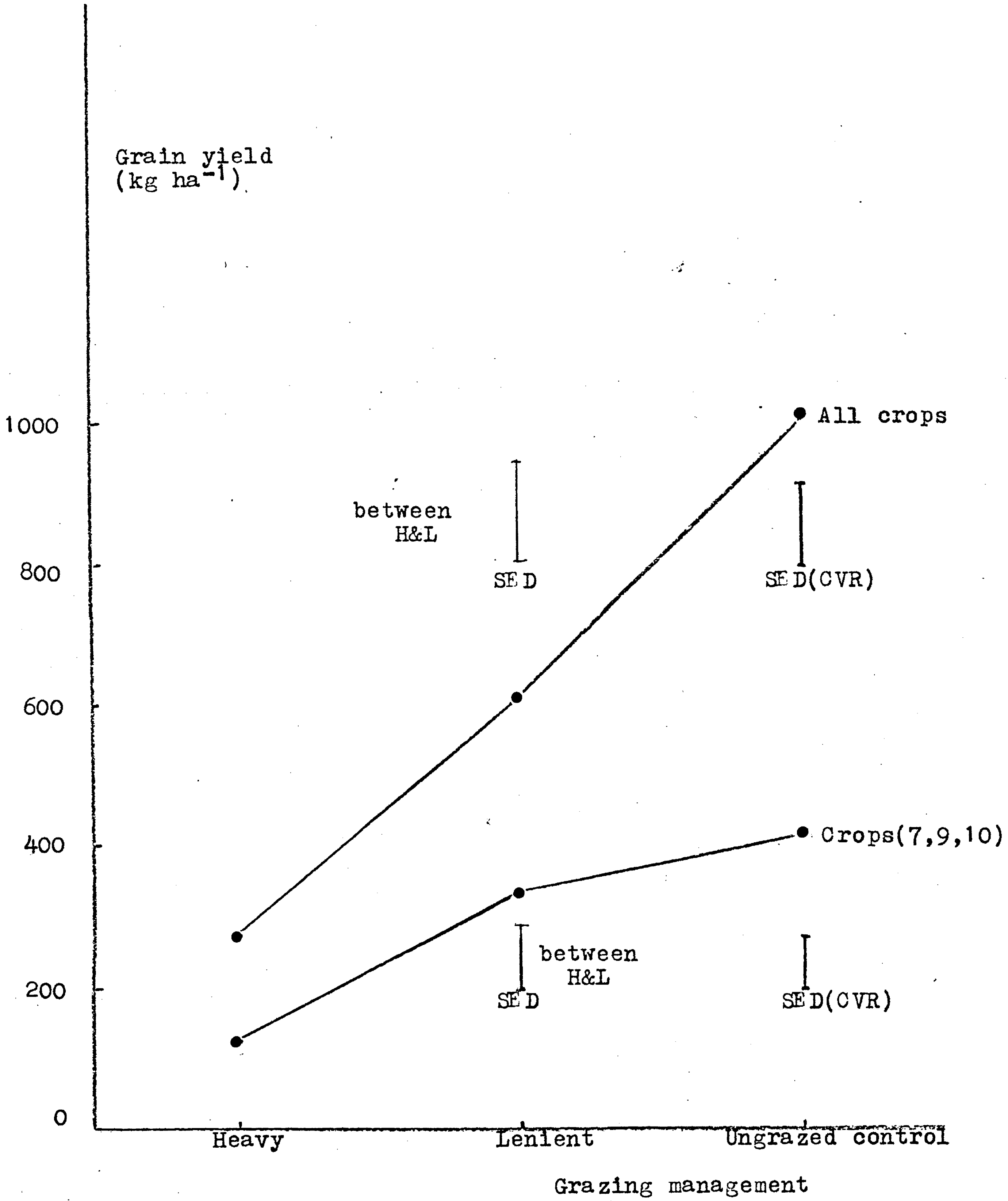


Figure 4.8: Effect of intensity of grazing on grain yield on the basis of pooled data from all crops 7,9,and 10 (H&L denote heavy and lenient grazing respectively)

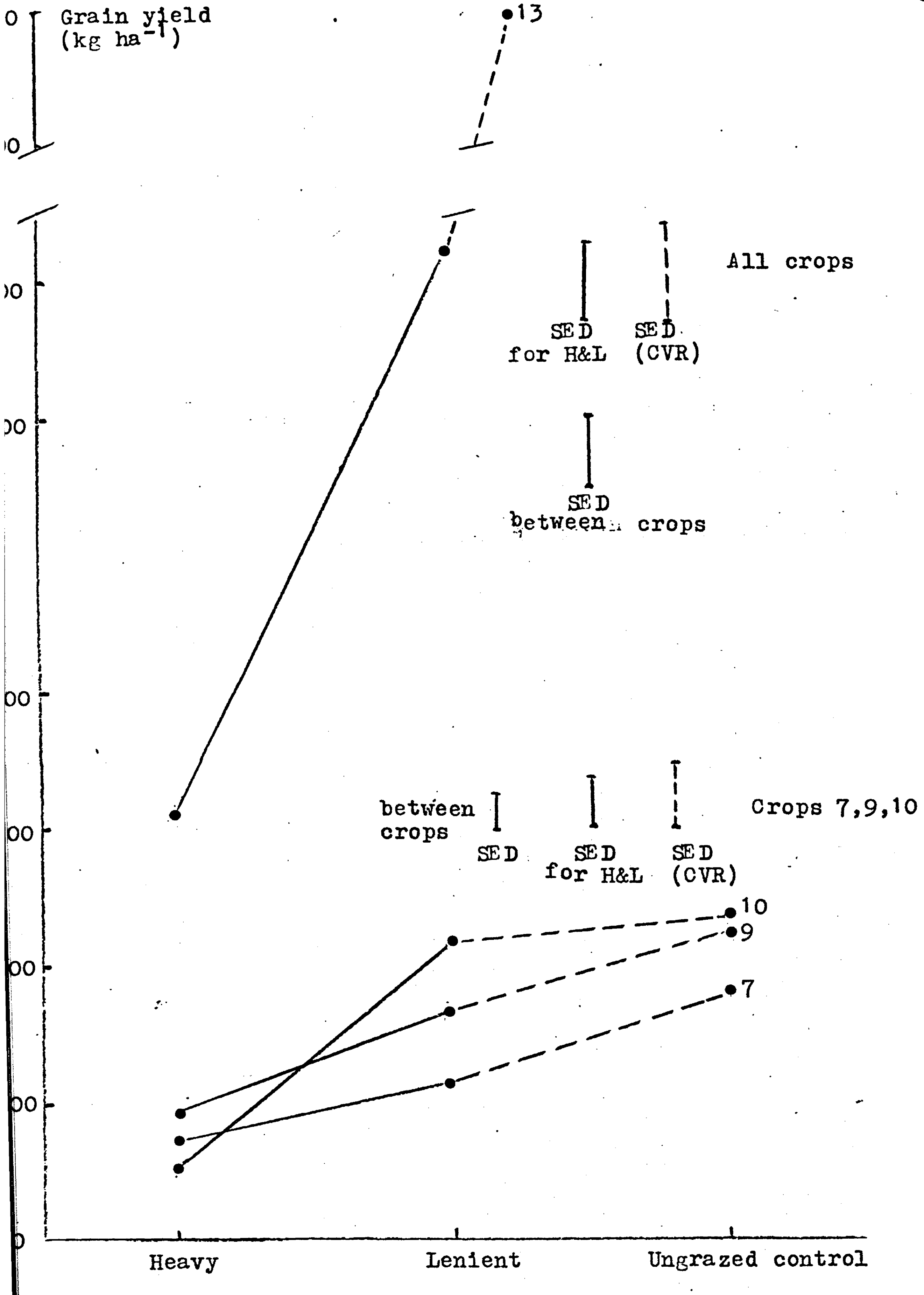


Figure 4.9: Effect of intensity of grazing on grain yield for individual crops (H&L denote heavy and lenient grazing respectively).

of yield (Table 4.4).

The length of the grazing period had no significant effect on grain yield (Table 4.3). As with the components of yield measured at flowering, there was a slight downward trend with grazing period up to 60 days but this increased sharply when grazing continued for 80 days (Figure 4.5).

DISCUSSION

There are inherent in grazing experiments many uncontrolled and uncontrollable variables whose consequences are often uncertain (Morley and Spedding 1968). Variability and/or unexpected interactions are likely to arise as a result of the influence of numerous external factors which, if important, may not always be measurable within the boundaries of a finite experiment. The experimenter is therefore compelled to accept some empiricism in his answers and he may extrapolate from his experimental results only to conditions in which the same set of variables and interactions operate.

Variability from external factors was also a feature of the present experiment. An unusually wet autumn restricted the area, and consequently the design, that could be used for the experiment. Continuing wet weather through to winter and spring led to waterlogging of many of the plots and abnormal conditions for cereal growth.

However some general conclusions may be drawn on forage yield and on the effects of grazing on regrowth and subsequent grain yield.

The differences in forage yield before the start of grazing

TABLE 4.4: Effects of grazing management on grain yield (kg ha^{-1})

Crops	Ungrazed	Length of grazing† (days)				SED	Grazing Intensity††		SED	Mean Grazed Plots	Reduction due to grazing (%)	
		20	40	60	80		H	L			H	L
Winter wheat	364	211	217	166	169		148	234		190.8	59.3	35.7
Spring wheat	443	209	309	240	296	259.8[a]	189	338	183.7[a] 225.0[b]	263.5	57.3	23.7
Barley	479	354	351	294	113		115	441		278.0	76.0	7.9
Oats	2792	1244	1067	1121	710		624	1446		1035.5	77.7	48.3
SED[c]			230.4				183.7					
Mean	1020.8	504.5	486.0	455.3	322.0		269.0	614.8		441.9	68.1	28.9

† Means of the two grazing intensities. †† Means of the four lengths of grazing, H & L denote heavy and lenient grazing

a - standard error of the difference between means within rows.

b - " " " " " " " for ungrazed crops and all grazed crops.

c - " " " " " " " within columns

seem to indicate that oats and barley are able to yield more early winter forage than wheat. Similar results have been reported by Crofts *et al.* (1958). However, this may reflect differences between the cereals in seasonal growth patterns rather than in overall forage yield. Lovett and Matheson (1974) compared forage yields of four cereals at two harvests in each of three years at Armidale. They revealed that the relatively poor performance of wheat at the first harvest was compensated for at the second one as a result of a more rapid development of leaf area index after defoliation.

Grazing Effects

The rate of regrowth between the end of grazing and flowering was independent of the extent of defoliation. As indicated by the analysis in Table 4.2 (at flowering - adjusted), the differences in yield at flowering were largely due to differences in residual dry matter at the end of grazing. Cook and Lovett (1974) conducted field and glasshouse trials to examine the growth responses of oats to defoliation and reported similar findings. Lovett and Matheson (1974) suggested, however, that the impact of severe grazing in removing leaf sheath material could affect the subsequent rate of production of leaf laminae. They also stated that if removal of new growth takes place before plants have fully recovered from an earlier defoliation, subsequent regrowth will be affected. Therefore a more severe grazing than the one practised in the present experiment or a set-stocked grazing system, might affect subsequent regrowth.

Although rate of regrowth was not affected by grazing, the reproductive performance of the crops was impaired by heavy grazing as shown by the significant reduction in number of live tillers and number of ears on the heavily grazed plots. Dann (1968), working with wheat (cv. Heron), showed that the number of productive shoots was significantly reduced when the plants were clipped to 1 inch above ground level, but not when clipped to 2 or 3 inches. Washko (1947) also reported that grazing reduced the number of productive tillers of a number of winter cereals, but his grazing treatment is not clearly defined.

Grain yield was generally affected by grazing but the length of the grazing period was of less importance than the intensity of grazing. There was, however, a trend towards yield reduction when the grazing period was extended for as long as 80 days (Table 4.4). Once differentiation has taken place, removal of the shoot apex will cause growth to cease on that tiller and subsequent regrowth requires the initiation of new tillers. The resulting 'second crop' may be beneficial for the grazing animal (Hyder 1972) but these later formed tillers often fail to produce inflorescences (Holliday 1956). Thus the more severe effect of the 80 day grazing period may have been the result of damage to the reproductive apex by trampling or grazing at a time when elongation was already taking place. Cutler *et al.* (1949), conducted a clipping experiment with winter wheat and concluded that:

(a) A moderate early defoliation may either increase or decrease both the yield and quality of the grain, this very much depending upon the weather conditions prevailing in spring.

(b) If grazing continues beyond 80 days before maturity date, significantly reduced grain yields can be expected.

In the present experiment the latest grazing treatment ended on September 10, that is, 97 days before the harvest date of barley and oats (December 12) or 111 days before that of the wheats (December 30). A direct comparison with Cutler's experiment cannot be made because his report does not specify whether the term "maturity" refers to physiological maturity or harvest date.

Intensity of grazing was the factor of prime importance but its effects differed widely between the four crops (Table 4.4). Oats which yielded best, was affected most by grazing; wheat lay at the opposite extreme with barley intermediate. Rapes did not recover from grazing to yield seed. Although these crops may be a viable proposition in terms of early winter forage supply, the varieties tested in this experiment proved to be unsuitable for dual-purpose use.

The superiority of oats was due to a greater number of grain per head and heavier grains (Table 4.5). The former attribute contributed more to make up the difference since its size differed from that of the other three cereals twofold, whereas the latter was only slightly higher.

Environmental and morphological factors in relation to crop response

As from late winter, some of the plots were intermittently waterlogged as a consequence of wet weather conditions which continued into most of the spring. Watson *et al.* (1976) studied the effects of conditions and intermittent waterlogging on growth and grain yield of wheat, barley and oats. They found that, at the conclusion of waterlogging, the growth of oats had been

TABLE 4.5: Effects of grazing management on grain yield components

Attribute and Crop	Ungrazed	Length of grazing† (days) 20	40	60	80	SED	Grazing intensity†† H	L	SED
No. of grains per head†††									
Winter wheat	19.2	14.2	17.0	17.8	7.6		12.7	15.5	
Spring wheat	18.1	13.8	11.8	13.8	13.4		11.8	14.6	2.49^{a}
Barley	18.5	18.3	18.0	18.9	11.7	3.52^{a}	14.8	18.7	3.04^{b}
Oats	56.5	39.7	29.5	39.8	24.8		27.8	39.1	
SED			2.98^{c}				2.49^{c}		
Mean grain weight (mg)†††									
Winter wheat	27.1	24.3	26.5	25.8	22.9		22.7	27.0	
Spring wheat	25.1	24.9	21.5	26.9	23.9		23.6	25.0	1.84^{a}
Barley	23.9	24.1	22.5	24.3	18.7	2.61^{a}	21.5	23.3	2.26^{b}
Oats	31.8	31.1	30.9	30.2	26.9		27.9	31.6	
SED			1.82^{c}				1.84^{c}		

† These figures are means of the two grazing intensities

†† These figures are means of the four lengths of grazing, H & L denote heavy and lenient grazing

††† These figures are means of 20 heads

a, b, c denote the same as in Table 4.4

affected more than that of the other two cereals. But when waterlogging ceased, oats recovered better than wheat or barley and yielded more grain.

Therefore, another reason for the higher oats grain yield may be that, by means of its resistance to waterlogging, it was the only crop able to realize its potential for grain production. The unusually low grain yields of wheat and barley on the ungrazed plots suggests that waterlogging may have impaired their performance.

Reference was made earlier to the fact that differences were found between crops in susceptibility to grazing. This has been reported to be associated with the position of the growing point at time of grazing (Washko 1947). The crops used in this experiment have different growth habits. The oats and barley varieties have an erect growth habit, WW31 spring wheat is semi-postrate (Ferns *et al.* 1975) and M1313 winter wheat is a postrate experimental variety (Dann, personal communication). Crops having an erect growth habit usually mature early and consequently will have their growing points located higher than those having a postrate one. This makes the plant more susceptible to defoliation by increasing the likelihood of the shoot apex being damaged by the grazing animal. The varying reduction in grain yield caused by grazing (Table 4.4) may then have been due to differences in growth habit between the cereals. This emphasized the importance of selecting the appropriate species and/or varieties to be used for dual-purpose practices.

Comparison of parameters for defining grazing treatments

It was postulated in the Introduction that the effects of defoliation could better be assessed by defining it in terms of green herbage remaining at the end of grazing. Some experimental support is provided by the work of Davidson (1965). He studied the effect of leaf area control on yield of wheat and concluded that 'presumably through its control of the growth of the shoot apex, leaf area prior to ear emergence exerts a major influence on the size at emergence of the ear and its component parts, and ultimately on grain yield'. Leaf area and weight of green dry matter have been reported to be linearly related (Brougham and Glenday 1967). Such a postulate would be particularly important when crops having different growth habits are to be compared. If two different crops, one erect and the other postrate, were defoliated to the same height at a time when their yields are equal, the erect one would have less remaining herbage than the postrate one. And if the effects of defoliation were then assessed on this basis, the individual crop responses are likely to be quite dissimilar. It would be difficult to tell whether the different responses were due to differences in the intrinsic capacity of recovery from defoliation or to the crops being severed to a different extent, that is, to non-comparable defoliation treatments. The latter seems to be a more adequate answer, for different levels of residual herbage represent different potentials for growth and consequently different patterns of recovery. Height of defoliation, however, may be important at a later stage of development in relation to the position of the shoot apex.

GRAIN YIELD PREDICTORS

Regression analysis was used to investigate the relationship between a number of variables and grain yield. Linear, curvilinear and multiple linear regression equations were fitted by the least square method and the 'goodness of fit' evaluated by means of the R^2 statistic (Snedecor 1965, p. 420) (Table 4.6). All equations involving a single variable were fitted through the origin on the assumption that zero level of the independent variable would result in zero yield. Winter wheat, spring wheat and barley responded somewhat similarly to grazing, whereby their data was pooled and analysed separately from that of oats. Weight of green material at the end of grazing, weight of green material at flowering and number of ears per unit area at flowering were the variables studied on single or multiple relationships involving two or all of these three variables. A number of curvilinear regression equations were fitted to the data and on the basis of 'best fit' the following exponential function was selected:

$$Y = b*(1 - e^{-cx})$$

where Y = predicted grain yield;

b = constant representing the value of 'Y' when the curve becomes asymptotic;

c = constant associated with crop response.

$1 - e^{-cx}$: This term is a useful indicator of the proportion of the maximum grain yield obtainable from a given level of the independent variable.

The multiple linear regression equations added very little to the predictive value of the linear regressions due to the fact

TABLE 4.6: Comparison of single and multiple relationships between a number of variables and grain yield

Grain yield predictor	Linear regression R^2 (%)†		Curvilinear Regression					
			7-9-10			13		
	7-9-10*	13*	b	c	R^2 (%)	b	c	R^2 (%)
(1) Green DM End of Grazing (DME)	37.1	62.2	450.8	0.0015	87.7	2808.0	0.0013	91.5
(2) Green DM at Flowering (DMF)	66.4	71.3	1512.0	0.0001	91.9	3460.0	0.0002	92.8
(3) No. Ears m^{-2} at Flowering (NE)	50.1	63.4	674.4	0.0040	88.8	5524.0	0.0015	89.5
	Multiple Linear Regression Multiple R^2 (%)							
	7-9-10	13						
(4) DME + DMF	66.4	76.3						
(5) DME + NE	66.1	69.8						
(6) DMF + NE	68.6	72.8						
(7) DME + DMF + NE	71.1	76.4						

† R^2 represents the proportion of the total sum of squares of Y (variation) attributable to regression

* 7, 9, 10 and 13 denote winter wheat, spring wheat, barley and oats respectively

that the independent variables were generally highly correlated. Except for the relationship between weight of green material at the end of grazing and number of ears, the coefficient of correlation ranged from 0.61 to 0.81. Fitting the appropriate curvilinear model, however, resulted in a substantial increase in the proportion of the variation of 'Y' attributable to regression (Table 4.6).

The small differences in R^2 between the different curvilinear relationships mean that, for predicting grain yield, the weight of green material at the end of grazing can be as good a predictor as a direct measurement of a reproductive attribute, e.g. number of ears per unit area.

Estimates of the proportion of the maximum grain yield that can be expected from different levels of remaining herbage were made by using the curvilinear regression equation 1 (Table 4.6). For crops 7, 9 and 10, increasing the amount of residual green herbage from 100 to 1600 kg ha^{-1} increased the percentage of the maximum grain yield obtainable from 13 to 90%. In the case of oats, 1800 kg ha^{-1} of residual herbage were required to obtain 90% of maximum grain yield. Hence, leaving more than 1600 - 1800 kg ha^{-1} of green material at the end of grazing would not substantially increase grain production yet would limit the utilization of the forage for animal feeding.

The different shapes of the response curves to grazing (in equation 1 of Table 4.6, c = 0.0015 or 0.0013 for crops 7, 9, 10 and 13 respectively) confirm that susceptibility to grazing was a distinguishing feature between crops. The values of the b coefficients in the same equation clearly indicate that for any level of the independent variable oats will produce much more grain than any of the other three crops.

From these results it can be concluded that, even though a higher susceptibility to grazing may increase the penalty of grazing a crop, it is its absolute grain yield as well as the price of its grain which must be taken into account in assessing the merit of the crop. For example, in this experiment, a 10% greater reduction in oats grain yield would be more than compensated for by its higher absolute grain yield.

The use of these relationships in decision making problems and their application to the economic evaluation of different grazing management policies will be discussed in detail in Chapter 6.

PART C

INTEGRATION OF SIMULATION AND EXPERIMENTATION IN AGRICULTURAL RESEARCH

CHAPTER 5:

DESCRIPTION OF A MODEL OF A MIXED SHEEP-CROPPING SYSTEM

INTRODUCTION

The previous two chapters of this thesis have presented the results of field experiments on two specific parts of a grazing system involving a pasture and a crop. The overall project included the simulation of this grazing system in a computer model which was to provide a framework for testing the experimental information and which could be subsequently applied to specific problems of grazing management at the whole farm level.

The advantages of such an approach are:

(a) that it gives a clearer picture of the kind of experiment that may be required to answer subsequent questions about any part of the system in relation to its effect on the whole system, and

(b) it provides a way of testing the effects of varying levels of input variables. This might involve, for example, the comparison of a wide range of seasons or the evaluation of a number of alternative grazing policies on the output from both the pasture and the crop. This chapter and the next deal with the construction and operation of such a model.

The system to be investigated is a combined sheep-cropping system involving a mixed improved pasture and a dual-purpose winter cereal. The use of cereals for both grazing and grain has become a common practice among Australian farmers (Hennessy and Robinson 1975, Lovett and Matheson 1974) but the conditions under which such a practice can operate profitably have not, as yet, been investigated in relation to the whole system.

The objective of the simulation study was to build a mathematical model of this system, suitable for operation on an electronic computer, with the two-fold purpose of (i) gaining an understanding of the system's component parts and of the important interactions between them, and (ii) assessing the effect of such management variables as stocking rate, the proportion of land allocated to the crop, the proportion of sheep grazing on the crop and the severity of grazing of the crop on the productivity of the system, as evaluated by a gross margin objective function.

Having defined the objective of the model it was then necessary to decide on its structure, or in other words, what variables were to be included and at what level of detail the processes were to be simulated - subjects that were discussed in Chapter 2. As a result, the model was formulated to predict weekly pasture and crop growth from historical data for climatic variables, the liveweight changes and wool growth of sheep resulting from their intake of pasture and crop and the grain production from the crop. Economic returns were predicted from the sale of wool, lambs and grain and the profitability of the enterprise was assessed in terms of gross margin per hectare.

STRUCTURE OF THE MODEL

The general structure of the model was determined by the convenience of being able to develop and test the individual component sections separately before inserting them into the overall framework. The resulting model is therefore composed of a main program and a number of subroutines, each of which deals with a specific component of the system. From the author's experience this is, at least in the initial stages, a challenge to the modeller's skill for building into the individual sections enough flexibility for them to be assembled later into a single integrated model. Nevertheless, in this study, such a structure proved particularly convenient because it enabled work to proceed on those parts for which information was available while field experiments were in progress to obtain data for developing the remaining parts.

The relationships used in the model fall into three classes. Firstly, there are what might be called standard or accepted relationships, such as those relating to the nutritional requirements of animals for maintenance and weight gain. These were obtained from previously published information (e.g. A.R.C. 1965). Secondly, there are relationships which I have derived from raw data, either my own or other workers', and the predictive value of these relationships is indicated by R^2 figures. Finally, there are relationships for which there is, as yet, little quantitative data. In these cases mathematical expressions were calculated from curves that fitted the existing data and practical experience in the particular field. It was for this latter category that assistance was frequently sought from colleagues in the CSIRO Agricultural Systems Section. The model must then, to some extent, reflect the opinions of these scientists. This, however, is likely to be a feature of most complex simulation studies, as the individual modeller is unlikely to have the necessary expertise in all the disciplines involved.

The time step set for the model was one week and this was chosen as a compromise between realism and practicability. Some of the biological processes in the system might have been more adequately simulated on a daily basis, since there was sufficient information to do so. The amount of detail included in these parts, however, would have been out of balance with the approximations that had to be used where data were limited. Another consideration was that, in practice, grazing management decisions are not likely to be changed at intervals of less than a week. The starting point for each year of simulation is the first week in March.

The mathematical model was written in FORTRAN IV. A full listing of the computer program is given in Appendix A and a glossary of the names of the variables in Appendix B.

Climatic factors

The climatic environment is extremely complex and the factors involved can be regarded as a major source of variability in the performance of farming systems. The climatic factors are usually referred to as 'driving forces' due to the influence they exert on all the biological components of the system. A brief listing of the climatic factors that could be considered would include rainfall, temperature, light intensity, hours of daylight, potential evapotranspiration, wind, hail and frost occurrence.

Despite the importance of these factors, no standardized methodology has yet, as far as the author is aware, been developed to determine what climatic variables are to be included in a model and whether the values used are to be a sample of real data or generated data. There are cases in which the former decision may be readily determined by the specific aim of the model concerned. In a model of soil conservation policies (Dumsday 1971) rainfall amount, pan evaporation and an index for the erosive potential of storm rain were the three variables selected on the basis of their relevance to the purpose of the study. Or the decision can be influenced by the characteristics of the environment being modelled. A model of plant growth based on soil moisture may give good prediction in an arid environment (Jeffery 1975) as availability of water is likely to be the limiting factor throughout the year. In a cool temperate environment, however, light and temperature are likely to limit plant growth during late autumn, winter and early spring.

A variety of combinations of climatic factors has been used by different modellers (Byrne and Tognetti 1968; Freer *et al.* 1970; Goodall 1971; Jeffery 1975; McKinney 1972; Vickery and Hedges 1972; White 1975; Wright 1970) for 'driving' plant growth models. The final decision seems then to be a subjective one, although factors such as these mentioned above should be taken into account when making the decision.

Whether to use a sample of real data or generated data is a problem that has generated arguments for and against each of these proposals (Jeffery 1975; Phillips 1971; Wright 1970). The decision has been based on personal reasons (Jeffery 1975) or on the convenience of avoiding the complications involved in developing a realistic model for synthesizing climatic data (Wright 1970).

For the purpose of developing this model actual historical records were used. One advantage of this approach was that some of the simulation results could be compared directly with those obtained from the field experiments, by using as climatic inputs for the model the values recorded during the year in which the experiments were conducted. This at least gave some basis for assessing the validity of the model. Light, rainfall, temperature and pan evaporation were the climatic variables used in the model.

Soil factors

The role ascribed to the soil component of the model was that of a water reservoir for plant growth. Thus, the only soil characteristics considered were those related to soil moisture, and all the others were assumed to be not limiting for plant growth. Of course this is an oversimplification of the soil-plant subsystem, particularly with regard to soil fertility. The main reason for excluding soil fertility was that the model is concerned with a well established mixed pasture in which a stable level of fertility has been reached, and hence only maintenance applications of fertilizer are needed.

The soil component of the model was based on a non-calcic brown soil with a water holding capacity in the A horizon (30-35 cm) of 28 and 13 percent in volume at field capacity and wilting point respectively (McKinney, personal communication).

Evapotranspiration and soil moisture budget

Evapotranspiration is a physical process through which available soil moisture is lost into the atmosphere. The actual rate of evapotranspiration (ACEVAT) refers to the loss of water by a soil under vegetation and depends on the potential rate of evapotranspiration and soil moisture content.

Potential evapotranspiration (PEVAT) is the amount of water evaporated from the soil and transpired by the vegetation under conditions of freely available water. The rate of the process is primarily determined by environmental factors such as radiation and temperature, and represents the evaporative demand of the environment. PEVAT can be measured by using energy balance (Denmead and McIlroy 1970) or lysimetric methods (Denmead and McIlroy 1970; McIlroy and Angus 1964), or estimated from measurements of free water evaporation (Linacre 1963; Penman 1948).

The method used in this study for estimating the PEVAT figures was based on the relationship between PEVAT and pan evaporation (PANEVA). This relationship takes the form of the following equation:

PEVAT = f*PANEVA (Linacre 1963)

where f is the conversion factor.

Penman (1948) showed that this factor varies with season of the year and proposed the following values:

Midwinter	:	0.6
Spring and Autumn	:	0.7
Summer	:	0.8
Whole year	:	0.75

These seasonal factors were used in the model for the weekly estimates of PEVAT.

ACEVAT does not always keep pace with PEVAT because the ACEVAT rate decreases with decreasing soils moisture content and increasing PEVAT, at a given soil water content (Denmead and Shaw 1962). The average soil water content at which the actual rate falls below the potential will depend on the type of soil being considered, since the suction force developed in the root zone is related to the textural and structural characteristics of the soil (Gardner 1960).

An indirect approach was used in the model to estimate ACEVAT based on the relationship between evaporative ratio and soil moisture content developed by Keig and McAlpine (1969) for the Canberra area. In its original form this was a step function which was transformed into a continuous function by fitting the following exponential equation:

$$EVR = 1 - e^{-0.035*FSLMT} \qquad \text{(Fig. 5.1)}$$

where EVR = evaporative ratio (ACEVAT/PEVAT)

FSLMT = soil moisture factor expressing the percentage of the total soil moisture storage capacity contained by the soil in a particular week and is predicted from the following equation:

$$FSLMT = (ASLMT - WP)/TSLMT * 100$$

where ASLMT = Actual soil moisture content (mm)

WP = Soil moisture content at wilting point (mm)

TSLMT = Total soil moisture content (FC-WP in mm)

where FC = Soil moisture content at field capacity (mm).

The actual weekly figures for ACEVAT (mm) are derived from the EVR estimates by using the formula:

$$ACEVAT = EVR * PEVAT.$$

These figures of ACEVAT can only be regarded as a fairly crude approximation of reality since no allowance has been made for the variation in the relationship between EVR and soil moisture content as PEVAT changes. This has been studied by Denmead and Shaw (1962) who worked with a Colo silty clay loam soil and derived a number of curves for a range of potential transpiration between 6.4 and 2.0 mm 24 hr^{-1} (Figure 5.2). Although the importance of this factor is recognized, there were no experimental data available to me from which these relationships could be derived for the type of soil represented in the model.

A soil moisture budget was used to keep account of the week-to-week variation in soil moisture content. The available soil moisture

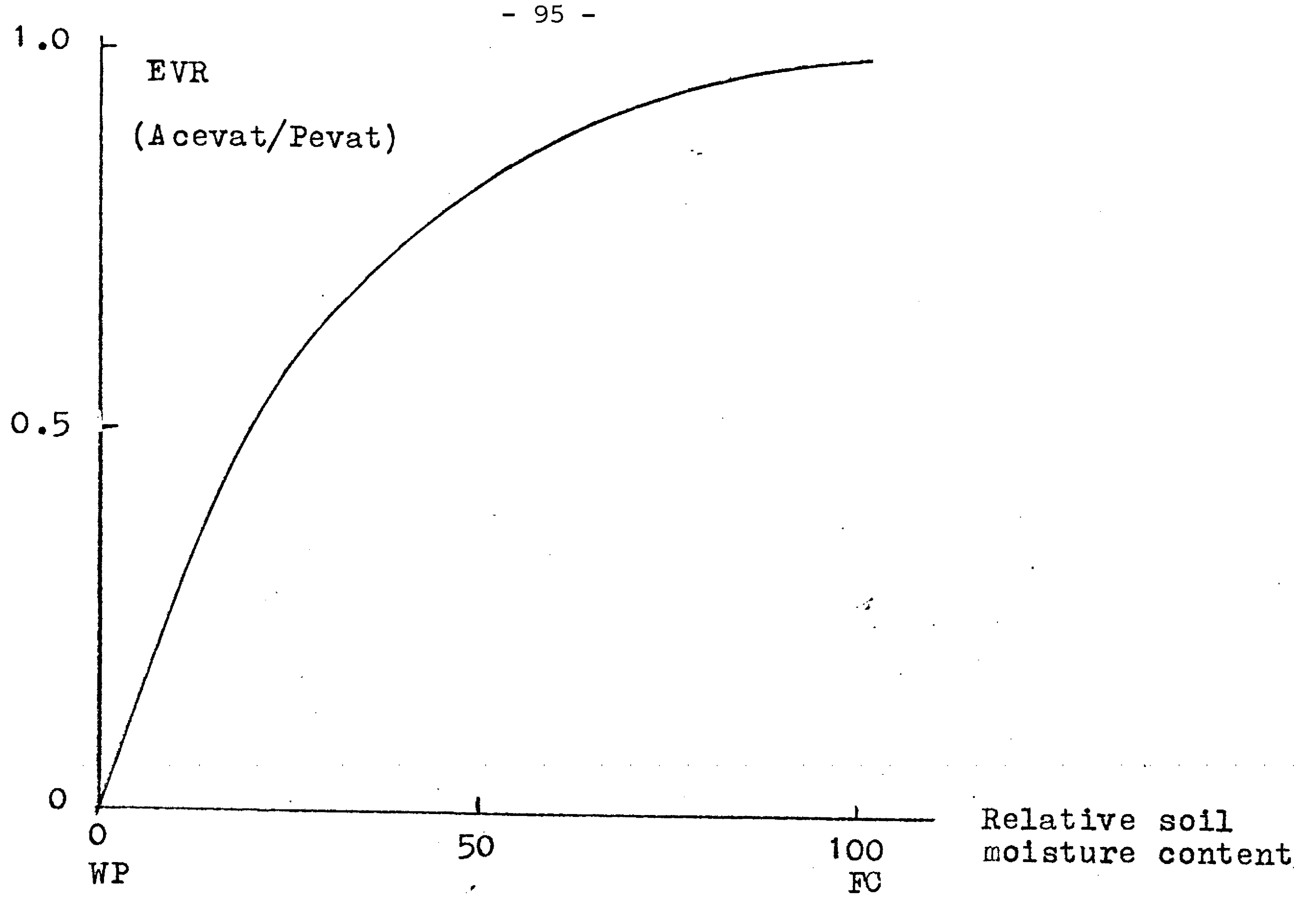


Figure 5.1: Relationship between relative evapotranspiration rate (EVR) and soil moisture content. WP = Wilting point, FC = Field capacity.

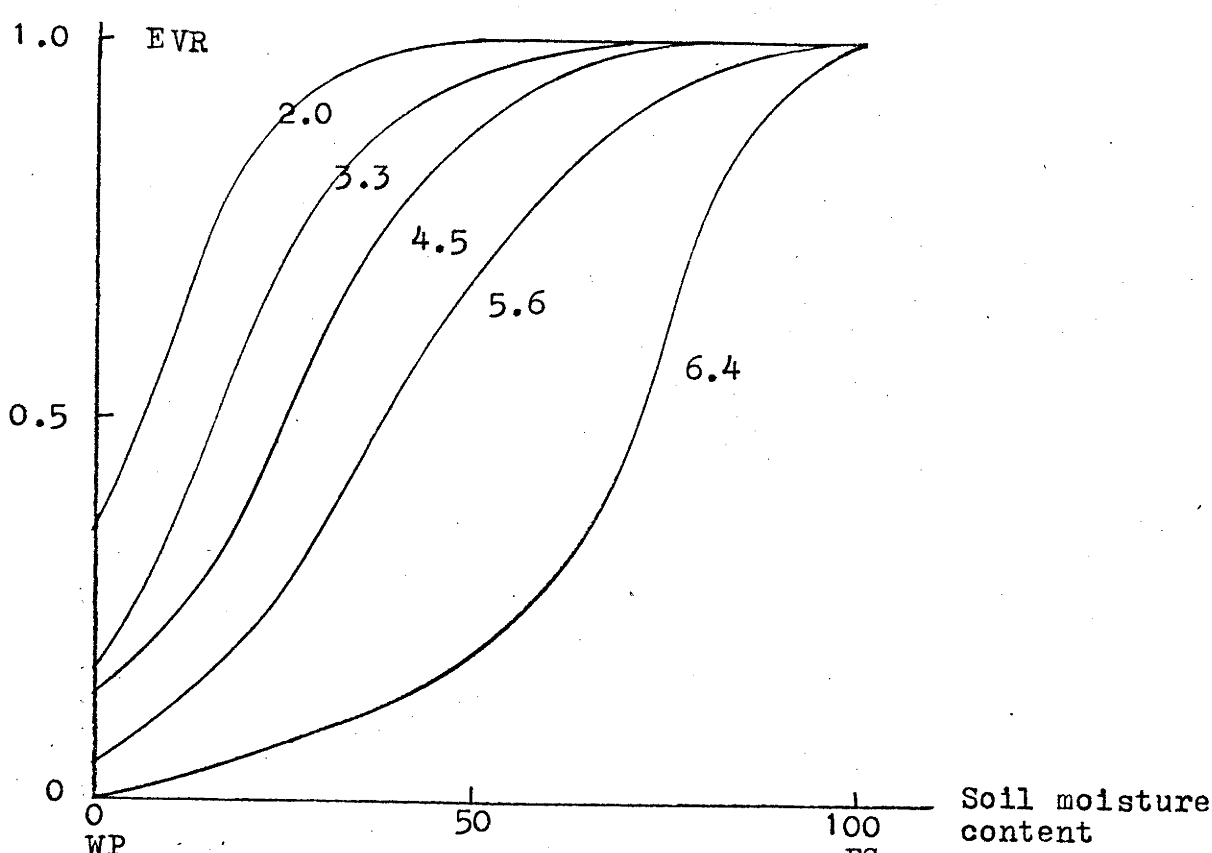


Figure 5.2: Relative transpiration rate (EVR) as a function of soil moisture content for different potential transpiration conditions (After Denmead and Shaw,1962).The curves represent days in which the transpiration rates at field capacity (in mm) had the value shown in the body of the figure.

for any week N was calculated from the equation below:

$$SLMT_N = SLMT_{N-1} + RAIN_N - WLOSS_N$$

where $WLOSS_N$ (mm) is the amount of water lost from the soil for week N and is considered to be equal to ACEVAT.

Run-off and deep percolation have been considered not to occur until the soil moisture content, as derived from the water balance equals the storage capacity of the soil at field capacity. Thus, any input of water in excess of field capacity is a loss to the soil-plant system.

The actual figures of weekly evapotranspiration and soil moisture content predicted by the model from a 14-year series of climatic data are given in Table 5.1.

Plant growth submodel

The objective of the plant growth submodel is to keep a weekly account of the quantity and quality of green and dry herbage on offer to the grazing animals. It is therefore necessary to calculate weekly growth rate as well as the weekly rates of the processes of senescence and decomposition.

The model was designed to generate a pattern of plant growth for a plant community under grazing by Merino ewes. The crops involved are a mixed pasture composed of *Phalaris tuberosa* and *Trifolium subterraneum* and a dual-purpose oats crop.

The most important variables determining the growth rate of a given sward were considered to be solar radiation, soil moisture, ambient temperature and the amount of herbage already present in the stand. It was assumed that these variables would affect both the pasture and the crop in a similar manner. Besides, as plant growth is being simulated under grazing conditions, the effect of

Table 5.1: Predicted values of actual evapotranspiration rates (ACEVAT, mm per week), absolute soil moisture content (SLMT, mm) and relative soil moisture content (,%).

WEEK	ACEVAT	SLMT	FSLMT	WEEK	ACEVAT	SLMT	FSLMT
1	7.96	40.3	2.8	27	8.99	84.0	100.0
2	5.77	39.4	.8	28	10.69	84.0	100.0
3	9.43	44.1	11.3	29	12.9	84.0	100.0
4	9.98	44.1	11.4	30	13.94	84.0	100.0
5	9.67	43.6	10.1	31	15.86	84.0	100.0
6	9.36	47.6	19.1	32	16.82	83.0	97.9
7	9.75	51.1	27.0	33	18.05	84.0	100.0
8	9.42	55.8	37.4	34	19.21	82.2	96.0
9	9.62	60.2	47.1	35	19.91	84.0	100.0
10	6.86	60.6	48.1	36	21.98	79.3	89.5
11	6.74	72.7	74.9	37	21.55	84.0	100.0
12	6.26	76.0	82.2	38	25.48	66.9	61.9
13	5.25	81.3	93.7	39	26.06	47.9	19.8
14	5.21	84.0	100.0	40	23.96	39.6	1.3
15	4.61	83.9	99.9	41	17.03	40.7	3.8
16	4.66	84.0	100.0	42	12.48	39.0	0.0
17	4.61	84.0	100.0	43	19.18	39.0	0.0
18	4.90	84.0	100.0	44	12.25	39.0	0.0
19	4.57	84.0	100.0	45	9.19	39.0	0.0
20	4.65	84.0	100.0	46	19.58	39.9	2.2
21	5.33	84.0	100.0	47	17.02	39.0	0.0
22	5.77	84.0	100.0	48	20.15	40.4	3.0
23	6.75	84.0	100.0	49	18.29	39.0	0.0
24	7.04	84.0	100.0	50	21.26	44.0	11.2
25	6.38	84.0	100.0	51	18.22	39.0	0.0
26	7.76	84.0	100.0	52	10.55	39.6	1.2

grazing on plant growth has to be accounted for. Defoliation by the grazing animal reduces the amount of herbage available, and as this is one of the variables affecting growth rate in the model, the feedback mechanism can be adequately represented.

Therefore, a practical approach appeared to be the definition of the potential plant growth rate for a certain level of herbage availability and time of year, and then the calculation of actual growth rate from this potential after taking into account the limiting effects of light, soil moisture and temperature.

Although the model is rather simple, the variables included seem to be sufficient to explain the main processes operating in this grazing system, so that a satisfactory pattern of pasture growth throughout the year can be generated. A flow chart describing the general structure and processes taking place in the plant growth submodel is given in Figure 5.3.

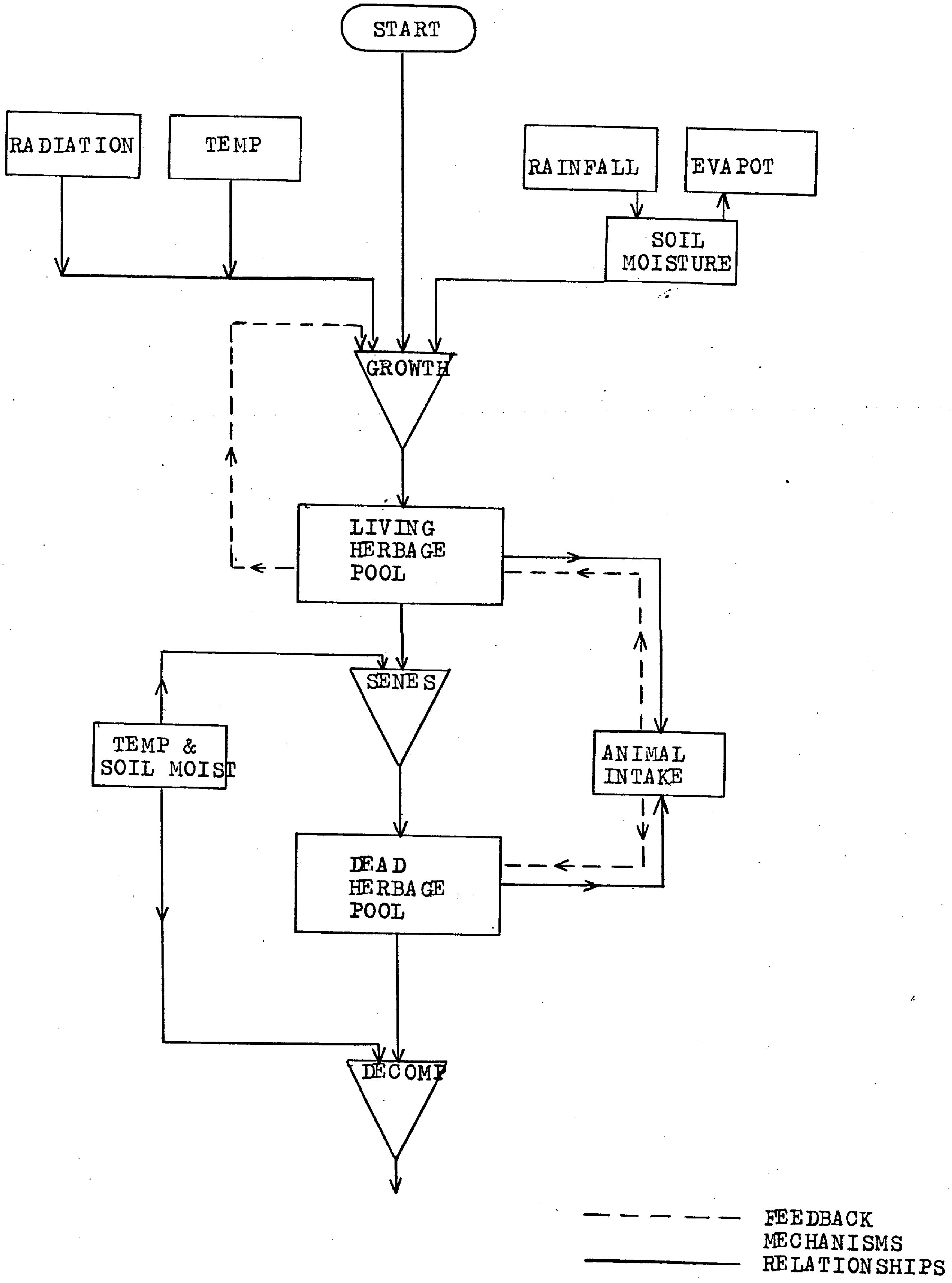
(a) An equation for plant growth

Growth can be defined as the progressive development of an organism, but there are several ways in which the development of a plant can be expressed. Growth may refer to the development of some specific organ or organs or to the plant as a whole, and it may be stated in terms of dry weight, length, height or diameter. Whether growth is given as the increase in dry weight, or in height of the plant, there is a fairly constant relationship between the measure of growth employed and time.

This relationship in an annual plant community is well represented by the equation of the generalized logistic growth curve below:

$$W = A/(1 + be^{-kt})$$ (Tisdale and Nelson 1966; Richards 1969)

Figure 5.3: Diagram of the structure of the pasture submodel



where W = accumulated herbage dry matter

A = maximum size attainable by W

t = time

b,k = constants

According to this equation: (i) relative growth rate is linearly related to the quantity of herbage present (Richards 1959), and (ii) growth rate is maximized when the herbage availability is half of the potential or ceiling yield (point of inflexion). However, experimental data from pasture growth experiments (Davidson and Donald 1958; Brougham 1959) suggest that maximum growth rate is obtained when pasture availability is less than 50 *per cent* of ceiling yield. Furthermore, Jeffery (personal communication) re-analyzed data of Brougham (1956) and showed that relative growth rate is not linearly related to the weight of herbage present but it declines curvilinearly as herbage availability increases.

If these two assumptions are valid, then pasture growth is not adequately described by the logistic equation. Therefore, a more appropriate curve was used so that a more precise representation of the growth process of both the pasture and the crop could be obtained.

Richards (1959) modified the basic von Bertalanffy equation and developed a flexible growth equation which provides for different growth patterns to be generated by changing the value of the constant in equation (1) below. In addition to this, relative growth rate as derived from Richards' equation is curvilinearly related to weight of herbage available (W) for values of 'm' less than unity (equation (2)).

Potential pasture growth rate, under non-limiting environmental conditions, is sensitive to the amount of herbage available, or as pointed out by Donald (1951) to the leaf area index (LAI) values. At low levels of herbage availability the LAI values will be insufficient to fully intercept incident light, and consequently submaximal growth rates can be expected. On the other hand, large amounts of herbage will form a thick and crowded canopy in which shading effects and the appearance of parasitic leaves in the lower layers are factors that lower the efficiency of growth.

It has also been discussed in the previous section that changes in stocking rate will rapidly be reflected in changes in availability of herbage. It therefore seemed more appropriate, to express potential growth rate in terms of the quantity of herbage available, rather than expressing weight of herbage as a function of time.

The relationship between potential growth rate and herbage availability is represented by the differential equation (after Richards 1959):

$$\frac{dW}{dt} = k\ W\ \left((A/W)^{1-m} - 1\right)/(1 - m) \qquad (1)$$

where W = amount of herbage available

A = ceiling yield

t = time

k,m = constants

and the relative growth rate is:

$$\frac{1}{W} \cdot \frac{dW}{dt} = k\ \left((A/W)^{1-m} - 1\right)/(1 - m) \qquad (2)$$

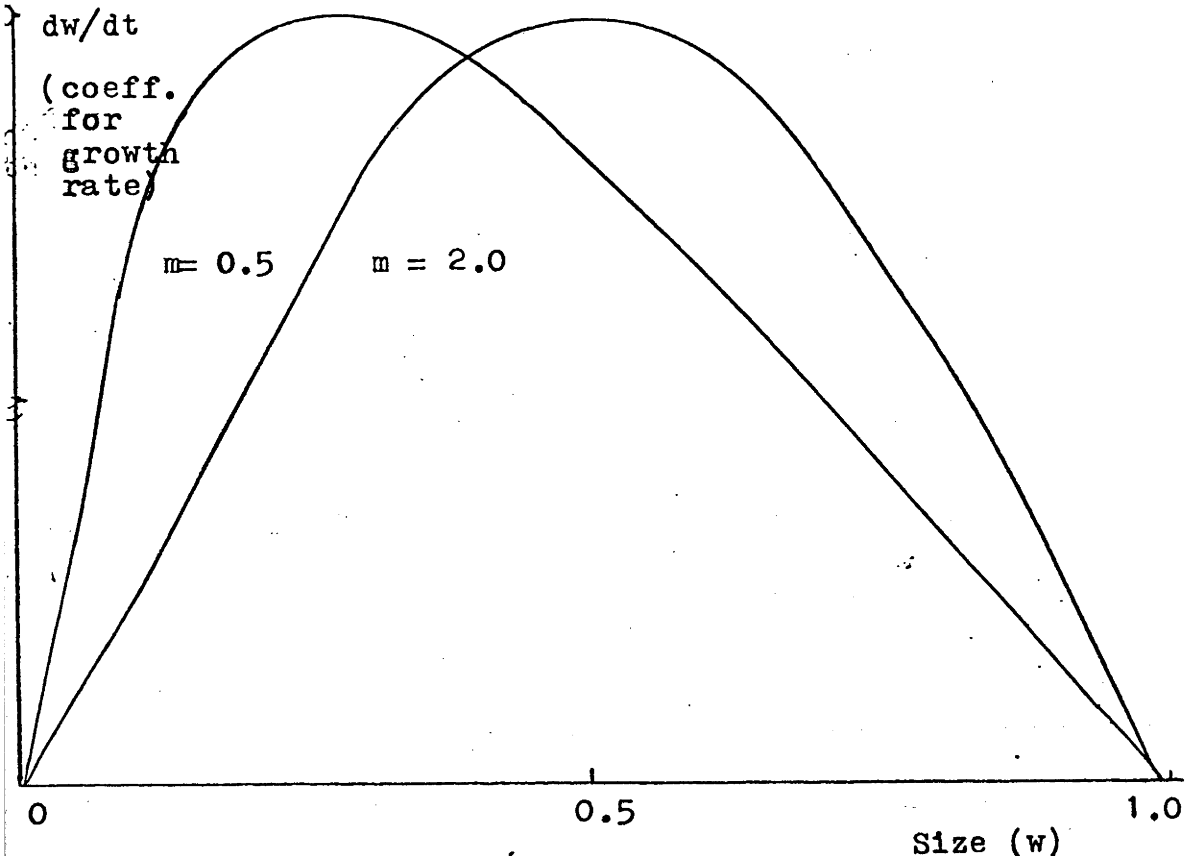
The constant m needs a little more consideration since the symmetry of the growth curves that can be obtained from this equation depends solely on the value of m. For values of m ranging between 2 and 0 the shape of the curve changes from the logistic to the monomolecular (an exponential without a point of inflexion), passing through the Gompertz curve when m equals unity. Furthermore, this constant determines the proportion of the final weight at which the point of inflexion occurs, according to the formula

$$W/A = m^{1/(1-m)}.$$

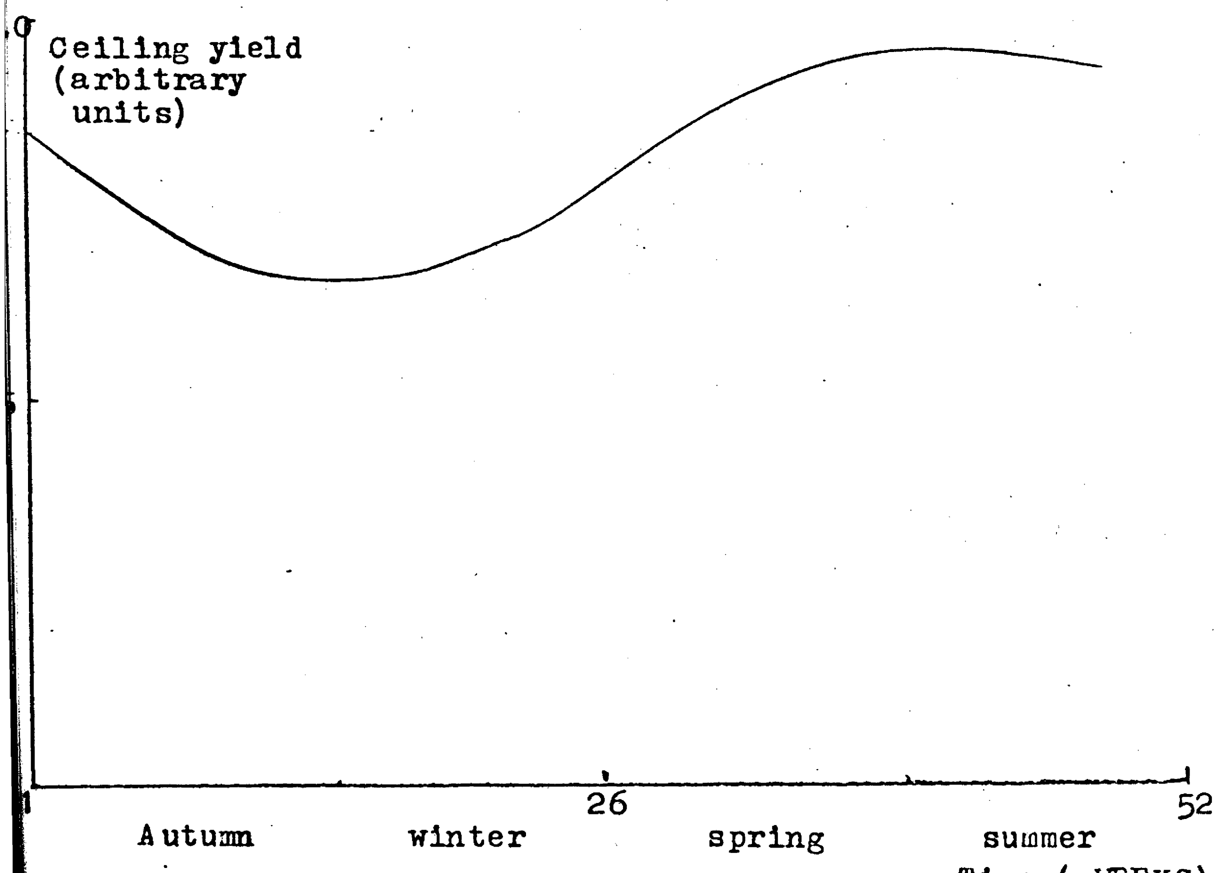
Crop growth was represented by means of a Richards function with m = 2 (i.e. the logistic curve) in which the point of inflexion occurs at W = A/2, that is, at half the value of the potential yield. For the pasture growth curve, a value of m = 0.5 was used, the point of inflexion being now at W = A/4. The relationship between dW/dt and W for curves having these values of m are shown in Figure 5.4.

These curves basically differ in the rapidity with which the point of inflexion is reached. Annual species growing from a limited source of reserves (the seed) will follow a different curve from a perennial species which has reserves readily available in the root system at the beginning of the season. Plants growing from seed tend to follow a growth pattern resembling the logistic curve which features a slow take-off and longer time for the maximum growth rate to be reached. Regrowth of a perennial species will follow a curve similar to that of Figure 5.4 with m = 0.5. This implies that the take-off will be steeper and that maximum growth rate will occur before half the ceiling yield is reached.

The rate of the growth process, as described by equation (1) will be determined by the herbage available (W) at any instant t and the ratio of maximum size attainable (A) to W. A is a measure of the "potentiality for growth", a potentiality defined by the genetic make up of the plant (Richards 1969). The values of the parameter A used in the model for the pasture and the crop and the procedure employed to derive the constant k can be found in Appendix C.



re 5.4: Relatioship beteween growth rate (dw/dt) and size (w) for differents values of the "m" parameter (After Richards,1959).



re 5.5: Seasonal variation in ceiling yield in response to the light environment (After Fitzpatrick and Nix,1973).

(b) Environmental effects

The interactions between the environmental variables and living organisms have been the subject of many volumes of published literature. The complexity of the endless chain of biological processes involved is outside the scope of this thesis and beyond the purpose of this model. Hence no formal literature review has been attempted and rather simple relationships have been developed, based on theoretical and experimental grounds, to simulate the effect of the environment on plant growth.

Three environmental variables are considered to directly affect plant growth in the model. They are incident radiation, temperature and the ratio of actual to potential evapotranspiration (evaporative ratio).

(i) Effect of light

The rate of photosynthesis of a leaf canopy is the result of complex interactions between the morphological and physiological properties of the plant and the physical properties of the incident radiation. Light intensity and light duration are the factors that will directly affect plant growth. The former is a measure of the rate at which energy is being incorporated into the plant machinery and hence influences the photosynthetic rate of the plant, whereas the latter acts mainly as a catalytic agent in timing the occurrence of developmental processes, e.g. flower induction.

In the absence of other environmental limitations the seasonal pattern of plant growth would closely follow that of the incident light, provided that efficient light utilization can be assured by maintaining leaf area index levels at or near optimal. In other words ceiling yield will be governed by light (Donald 1961, 1963).

On this assumption, the influence of light on pasture growth rate was accounted for by varying ceiling yield (A in equation 1) on a weekly basis according to the variation in total solar radiation, which depends on light intensity and daylength. A light index developed by Fitzpatrick and Nix (1973) for the Canberra area was used for this purpose in the model, and a sine curve with a maximum of 0.944 in December and a minimum of 0.639 in June was fitted. The equation defining the curve (Fig. 5.5) is:

$$\text{CLNYLD} = \text{CYMAX}*(0.791 + 0.153*\text{SIN}(0.121*(\text{WEEK} + 10) + 1.25)) \quad (3)$$

where CLNYLD = ceiling yield for week N

CYMAX = maximum ceiling yield

Maximum ceiling yield refers to the greatest size attainable by a plant community in a state of equilibrium with a non-limiting environment. At this stage, dry weight of living material per unit area is static, which means that the rate of respiratory losses equals that of photosynthetic gains. Information on the actual size of this parameter for different crops is by no means profuse, and the values used for the pasture and the crop are 8000 kg ha^{-1} (Brougham 1959) and 10000 kg ha^{-1} (Watson *et al.* 1963) respectively.

(ii) Effect of temperature

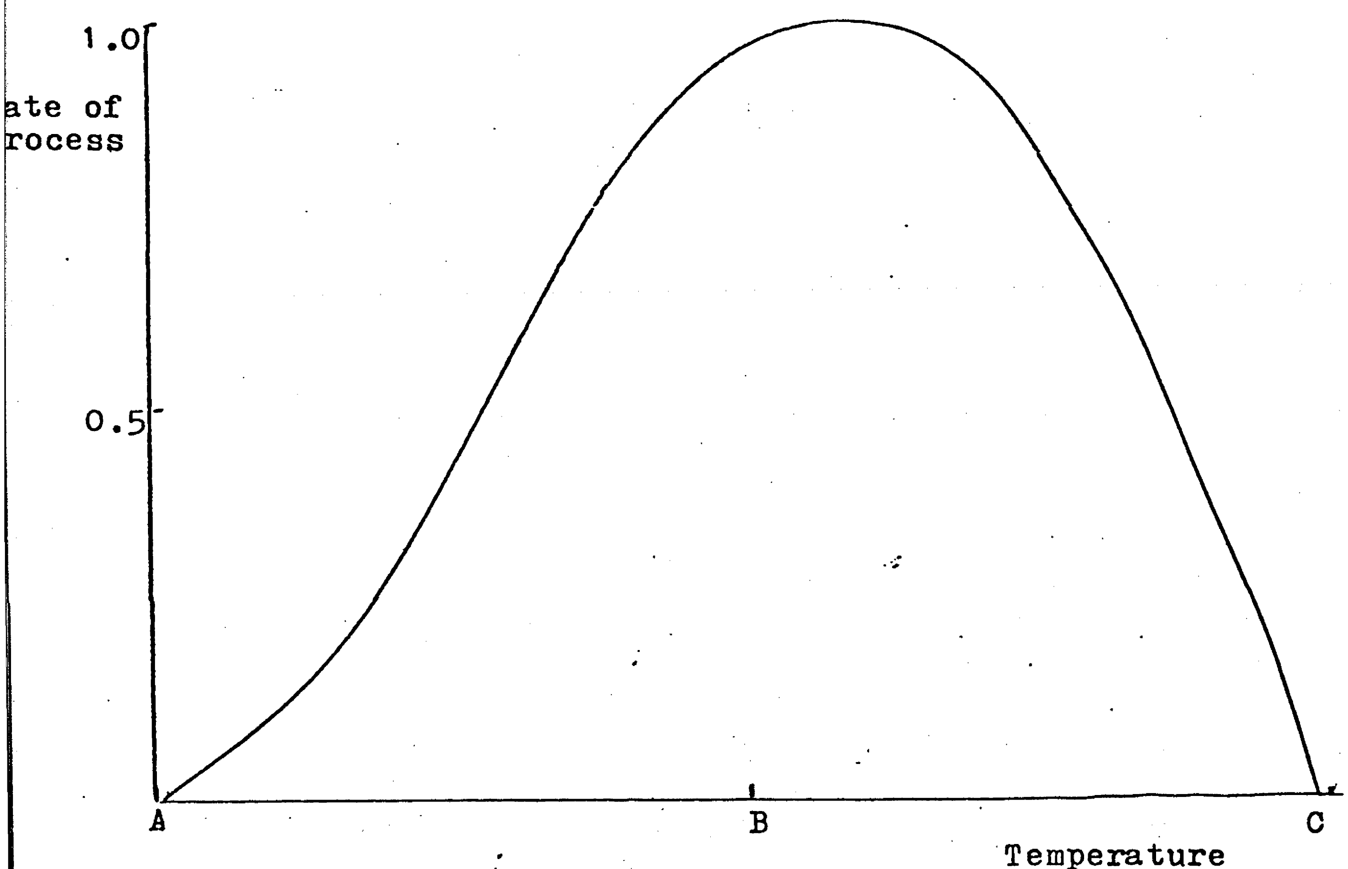
Temperature has a pervasive influence on the rate of plant growth because it affects the rate of all biophysical and biochemical processes involved in metabolism. The response of living organisms to variations in temperature follows a general pattern represented by the curve in Figure 5.6.

In general the rates of processes increase with increasing temperature; the Q_{10} for physical processes such as diffusion are between 1.2 and 1.3 and for enzymatic reactions between 1.4 and 2.0 (A - B) (Greulach 1973). However, when temperature rises above the optimum (B) enzyme inactivation begins giving rise to a decline in the metabolic activity (B - C). Furthermore, at temperatures much above optimum enzymes are denatured to such an extent that serious injury or death may result (C).

The effect of temperature on the various metabolic processes of plants in turn influences the rate of growth by determining the quantity and kinds of foods to be used in assimilation, the rates of synthesis of substrates, the degree of hydration of the cells and many other internal conditions and processes. However the rate of growth does not necessarily increase proportionally with the rates of metabolic activity, nor does it necessarily have the same range of optimal temperature. At the higher levels of environmental temperature growth may be severely checked because of such factors as desiccation, which is brought about by high rates of transpiration, and the fact that respiration increases more rapidly than photosynthesis with the rise in temperature (Greulach 1973).

Mitchell (1956) studied the effect of temperature on growth of several temperate pasture species. His data suggest that the optimum range lies between 17°C and 24°C, the maximum critical temperature at which growth comes to a standstill being 35°C, and the minimal critical temperature being 4°C (Greulach 1973; Brougham 1962).

In this work these values of weekly mean air temperature were



A = Minimum critical temperature
B = Optimum temperature
C = Maximum critical temperature
gure 5.6: General effect of temperature on the rate of processes in living organisms.

used to model the effect of temperature on plant growth by fitting a fifth polynomial in which maximum growth occurs at optimal temperature, and progressively declines towards either of the critical temperatures, reaching a point of zero growth when either of these two is reached. The curve was defined by the following equation:

$$TFG = 0.5844 + 0.2268*T - 0.0271*T^2 + 0.00197*T^3 - 0.000063*T^4 + 0.00000068*T^5 \quad (4)$$

where TFG = Temperature factor for growth

T = weekly mean air temperature.

(iii) Effect of availability of water

Plant growth is related in a general way to the amount of evapotranspiration that occurs during the growth period. As the word implies, evapotranspiration comprises two components - evaporation from the soil and transpiration from the vegetation. Evaporation from the soil contributes little to plant growth, except as increased environmental humidity might affect above ground parts of the plant. Transpiration, on the other hand, is directly involved on the growth of nearly all higher plants (Arkley 1963).

The same author analysed data from experiments in the literature and calculated new relationships by means of various equations, reporting in every case, a linear relationship between the amount of dry matter produced (Y) and the amount of water transpired (Tr) by a particular species of plant, under given environmental conditions of climate and soil fertility:

$$Y = k\ Tr$$

The regression coefficient k is a parameter that depends on the kind of plant, which may be expressed as the amount of dry matter produced per unit of water transpired. In oats varieties this parameter has been found to average 1.63 g/litre, and in barley varieties, 1.86 g/litre.

Water moves through the soil to the plant root and from the roots to the transpiring leaves following pressure gradients, gradients of suction (negative pressure) in the soil, and gradients of diffusion pressure deficit, DPD, in the plant. It is necessary to maintain a suction gradient between root and soil, if a given transpiration rate is to be kept. The capillary conductivities of soils decrease rapidly with increasing soil suction. Consequently, as the soil dries, large suction gradients develop between the root and the soil around it. Thus, to maintain transpiration in a drying soil the DPD in the leaves must continually rise so that the necessary DPD gradient between leaf and root is still present. The rise in DPD in the leaves is accompanied by a decrease in turgor pressure resulting in closing of the stomata, decline in the permeability of the plant to water flow and the transpiration rate must decrease.

This drop in the rate of transpiration has been found to affect leaf elongation of grasses (Turner, personal communication) and stomatal closure will determine an increased diffusion resistance into the leaf, which in turn will decrease the photosynthetic activity of the plant.

From this theoretical consideration it was assumed that when actual evapotranspiration, as limited by soil moisture content, fell below potential evapotranspiration, the growth rate of the plant was going to be checked.

In the present study, a linear 1:1 relationship between fractional dry matter production and the ratio of actual to potential evapotranspiration (EVR) is assumed (Fitzpatrick and Nix 1973; de Wit 1958).

The model used to assess the decline in the evaporative ratio with decreasing soil moisture is represented by the exponential function already presented in Figure 5.1.

Each of the equations used to estimate the influence of a certain environmental factor gives an "index of growth", ranging between 0.0 and 1.0, which expresses the limiting effect of that factor for a particular week. The combined effect of the environmental factors as a determinant of actual growth rate is quantified by the product of potential growth rate and the various indices for growth as follows:

$$GINC = GRMAX * TFG * SLMTFG$$

where GINC = actual growth rate (kg ha^{-1} week^{-1})

GRMAX = potential growth rate (kg ha^{-1} week^{-1}) as derived from equations (1) and (2)

TFG = temperature factor for growth (equation (4))

SLMTFG = soil moisture factor for growth from Fig. 5.1.

The equation for calculating GRMAX is:

$$GRMAX = 0.2625*W*((A/W)^{0.5} - 1.0)/0.5$$

(see equation (1) for the meanings of variable names)

(c) Senescence and decomposition

The amount of photosynthetically active tissue in a plant community is subject to dynamic changes controlled by the rate of production of new material and the rate of senescence and death of the plant organs. Similarly, the quantity of dry material present in a stand will be determined by the rate of decomposition, which in turn will affect the total accumulation of dry matter in the sward.

One of the factors involved in the transfer of green herbage to dry herbage is the leaf area index, or in other words, the amount of herbage present, since there is a linear relationship between the two. Measurements of the penetration of light into a sward have shown that the change from the phase of living matter accumulation to the phase of dead matter accumulation occurs shortly after the sward has become large enough to intercept nearly all daylight (Hunt 1965, Hunt and Brougham, 1966). This suggests that a "self-pruning" mechanism comes into operation soon after competition for light becomes severe, when old leaves at the base of the sward receive only small amounts of daylight.

The availability of water to the plant is another factor influencing the rate and onset of senescence. McWilliam (1968) states that the important factor influencing the expression of senescence appears to be the drying of the surface soil, which contains the bulk of the fine root system, and reported that plants grown in nutrient solution senesced and died when the potential of the solution was decreased to -3.5 bars.

Plant death may also be increased by high temperatures (Cocks, 1973), and in response to moisture stress senescence is accelerated as temperature rises (McWilliam 1968).

In the present model, the proportion of the green herbage dry matter (GP) which becomes senescent each week is calculated as a potential value (AFS) which increases with GP, to an upper limit of 1.0 when GP = 1500 kg ha^{-1}, and a function (TGDF) of soil moisture and temperature according to the following equations:

ASF = 0.00067*GP

$$TGDF = (1.0 - 0.99*SLMT)*(1.0 - e^{-0.003*T^2})$$

where SLMT = soil moisture content (mm)

T = mean weekly air temperature (^{o}C)

Therefore the weight becoming senescent each week (AMTSNDP) = GP*AFS*TGDF.

In the case of perennial species of *Phalaris* there is a sudden change in the pattern of senescence of leaves after flowering occurs in early summer. However, senescence is not likely to increase greatly if the soil remains moist during the first four weeks after the commencement of flowering. But if the water potential of the soil falls below -3.5 bars (49.5 mm for the soil under study) or flowering is in its fifth week, senescence will increase sharply and most of the green material will dry out in approximately two to three weeks (McWilliam 1968). Week 40 was considered to be the time of the year when phalaris flowers in the Canberra region and the rate of senescence of the pasture (TGDFP) then becomes:

$$TGDFP = 0.5*WEEK - 1.5$$

when Week > 40 and SLMT $\leq$ 49.5 mm

or Week > 40 + 4.

The same phenomenon was considered to apply to the crop but, in this case, the rate of senescence was fixed at a constant value of 15 *per cent* per week after the start of flowering in week 36.

Decay and decomposition is largely the result of microbial and invertebrate activity. As in most biological processes it could be predicted that the rate of decay would increase with an increase in temperature and humidity.

Wiegert and Evans (1964) in a study of the disappearance of dead vegetation on an old field in Michigan, concluded that rates of disappearance differed with time of year. This was attributed to marked seasonal fluctuations in temperature and rainfall. On the upland the rate varied from 8.4 mg/g per day to 1.3 mg/g per day, and on the swales from 13.6 mg/g per day to 1.8 mg/g per day.

The model assumes decay rate to be a function of temperature and soil moisture which is defined by the equation:

$$\text{DECRATE} = 0.08*(o.0189*\text{SLMT} - 0.587)*(1.0 - e^{-0.0174*T^2})$$

where DECRATE = decay rate (kg $kg^{-1}week^{-1}$)

SLMT = soil moisture content (mm)

T = temperature (^{o}C)

0.08 = maximum weekly decay rate (Wiegert and Evans 1964).

According to this equation decay rate has a minimum value of 1 *per cent* per week when humidity and temperature are not favourable for the decomposition process to take place, increasing towards a maximum of 8 *per cent* per week as temperature rises and soil moisture approaches field capacity.

High yields of herbage further increase rates of decomposition (Hutchinson 1971). Reduced light penetration and moisture conditions within a dense canopy are likely to favour the decomposer population. The change in decay rate (AMONTFD) as total herbage yield increases is approximately described by the equation:

$$\text{AMONTFD} = 0.99 + 1.03*(1.0 - e^{-0.067*((GP + DP)/1000)^2})$$

where GP = green herbage yield (kg ha^{-1})

DP = dead herbage yield (kg ha^{-1})

Animal production sub-model

Merino breeding ewes form the single class of animals which is used to simulate pasture and crop grazing. Some other models have divided the breeding animals into classes (Jeffery 1975) or even further, into cohorts (White 1975), but given the simplicity of the other sections of this model further development of the sub-model seemed unnecessary.

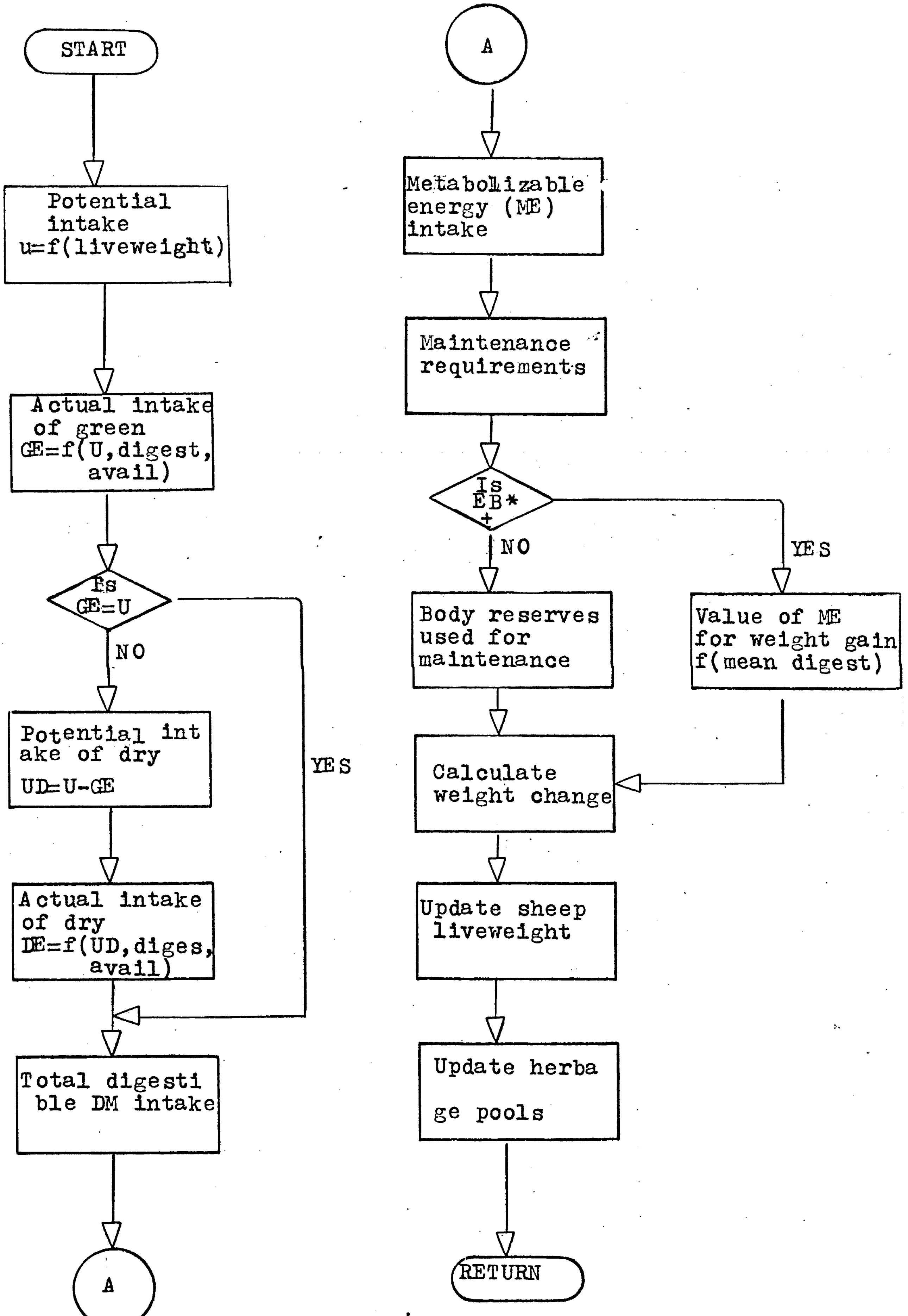
The model calculates weekly intake of pasture and crop (subroutines EATP and EATC respectively), liveweight change (subroutine WEIGHT) and wool production of the ewes (subroutine WOOL). The value of lamb production is estimated indirectly by function VALAMB, which predicts it as a function of ewe liveweight. Movement of sheep to and from the crop and adjustment of grazing pressure on the crop are controlled by subroutine MANAGE. A flow-chart of the animal sub-model is shown in Fig. 5.7.

The potential intake of forage dry matter (DM) is predicted from liveweight and this potential level is then modified for the availability, defined as the weight of forage DM (kg ha^{-1}), and the digestibility of both the green and dry fractions of the forage. From the actual intake, the losses in digestion and absorption are deducted to compute the metabolizable energy (ME) intake. The amount remaining after the energy cost of maintenance has been met, is used for liveweight change according to the energetic value of liveweight increment and the efficiency with which ME from the particular diet is used for anabolism.

(a) Intake of food by the animals

Voluntary intake is generally defined as the amount animals will eat when an excess of 15 *per cent* is offered (Blaxter *et al.* 1961). Its importance in determining the level of an animal's nutrient intake has been repeatedly stated (Raymond 1969, Waldo 1969) and yet farm feeds have been evaluated much more extensively for energy

Figure 5.7: Flowchart of the animal sub-model.



* EB = Energy balance

content, digestibility, protein content and even mineral composition (N.R.C. 1964, A.R.C. 1965) than for intake (Waldo 1969).

Over the past 20 years it has been advanced that there is a broad distinction between the mechanisms controlling intake by ruminants and by non-ruminants. Blaxter *et al.* (1956), Balch and Campling (1962) and Conrad *et al.* (1964) have suggested that the capacity of the digestive tract limits intake of forages by ruminants, whereas maximal intake by non-ruminants would be related to an energetic satiety, as indicated by levels of blood metabolites (Raymond 1969). On the basis of the 'rumen fill' theory, it has been suggested that mean values of dry matter intake could be predicted for animals of a certain size, age and productivity.

However, animal variability in voluntary intake of forages (Blaxter *et al.* 1961, Heaney *et al.* 1968) and variations for different diets make these mean values of doubtful use for predicting nutrient intake by grazing animals. Yet intake prediction in a livestock model is essential for the understanding and appraisal of a grazing system.

The voluntary intake of forages has been predicted from the capacity of the rumen (Rice *et al.* 1974) or as a function of liveweight, a relationship which is usually expressed as

$$I = aW^b$$

where I = voluntary intake

W = live weight

a & b = constants.

The value of b, which determines the "metabolic size" of the animal, is still a matter for discussion (Waldo 1969). Published values have varied from 0.6 to 1.0 but part of this difference may have resulted from differences in body condition at the time of weighing. The function above does imply a curvilinear relationship between intake and weight, but the results of Hadjipieris *et al.* (1965) and Langlands (1968) suggest a faster rate of decline in intake per unit liveweight as the animal approaches its mature weight, with a decline in absolute intake above this point.

For this reason, a quadratic relationship developed by F.H.W. Morley (personal communication) was used in this model to describe the relationship between dry matter intake and liveweight:

$$U = W*(60.0 - 0.6*W) \qquad (1)$$

where U = potential intake (kg DM day^{-1})

W = liveweight (kg)

The shape of this relationship is shown in Fig. 5.8.

This upper limit of intake (U) would be reached provided that no other factor limited intake. However feeds normally offered to ruminants are of varying quality and of varying availability when the animals are grazing pasture. Digestibility (as a measure of food quality) and the weight of herbage per unit area (as a measure of availability) have been proposed as the main factors controlling the voluntary intake of food by ruminants (Blaxter *et al.* 1961, Balch and Campling 1962, Langlands 1968, Raymond 1969).

It is now generally accepted that ruminants will consume more energy as ration digestibility increases, until their energy requirement is met. Once this point is reached, a further increase in digestibility may result in a decrease in intake (Conrad *et al.* 1964). Blaxter *et al.* (1961) conducted feeding trials with long

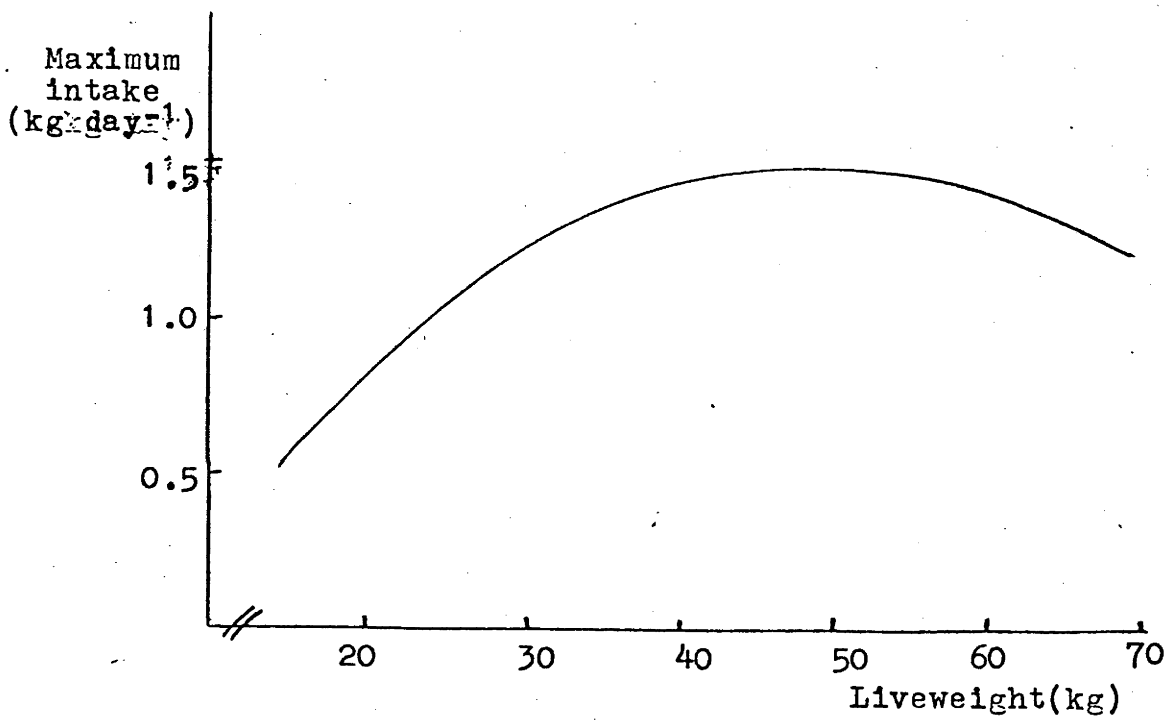


Figure 5.8: Potential dry matter intake relative to liveweight of Merino sheep

fodder of different digestibilities and concluded that sheep will eat none of a food that has an apparent digestibility of 30 *per cent* and that intake increases with increasing digestibility to reach a peak at an apparent digestibility of 75 *per cent*. Conrad *et al.* fed dairy cows with rations ranging between 52 and 80 *per cent* digestibility and found that the intake of digestible dry matter levelled out at 66 *per cent* and remained almost constant to 80 *per cent* digestibility.

The results of Blaxter *et al.* are incorporated in the function used by F.H.W. Morley (personal communication) to describe the relationship between dry matter intake (as a proportion of potential intake) and digestibility. This function is used in the present model; it is illustrated in Fig. 5.9 and its mathematical expression is as follows.

$$\text{APID} = 2.0*(1.0 - \text{EXP}(-(0.65 - \text{ABS}(\text{D} - \text{DM})))) \qquad (2)$$

where APID = actual intake as a proportion of potential intake

D = coefficient of digestibility

DM = digestibility at which intake reaches a maximum.

This is the only index of food quality used in the model and one disadvantage is that other characteristics of the food which may have an effect on intake are not always related to digestibility. For example, at the same level of digestibility, legumes, which contain less cell wall material, are consumed in greater quantities than grasses. Van Soest (1965) related several chemical components of forages to their intake and found that the best relationship was with total plant cell wall, intake decreasing as cell wall rose.

Herbage availability was the other factor considered to limit

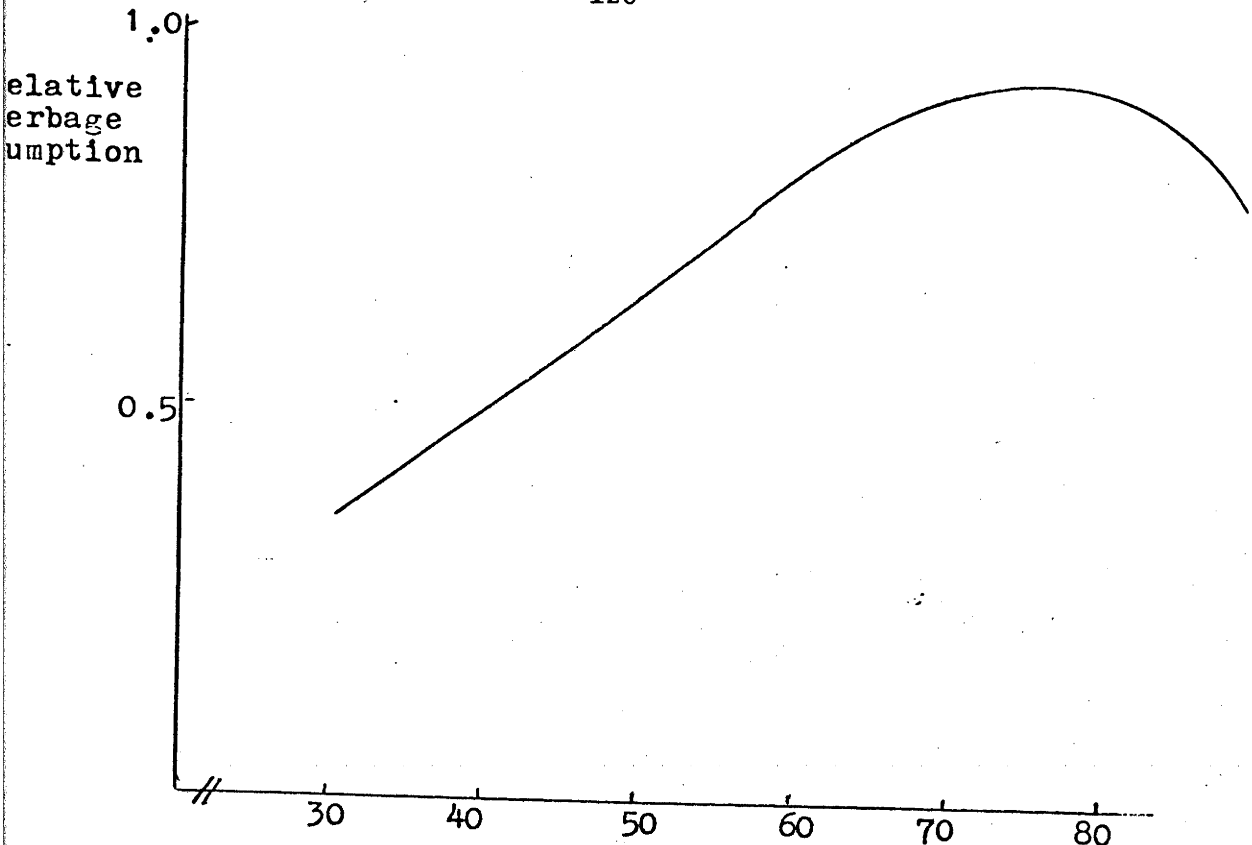


Figure 5.9: Relationship between relative herbage consumption and digestibility

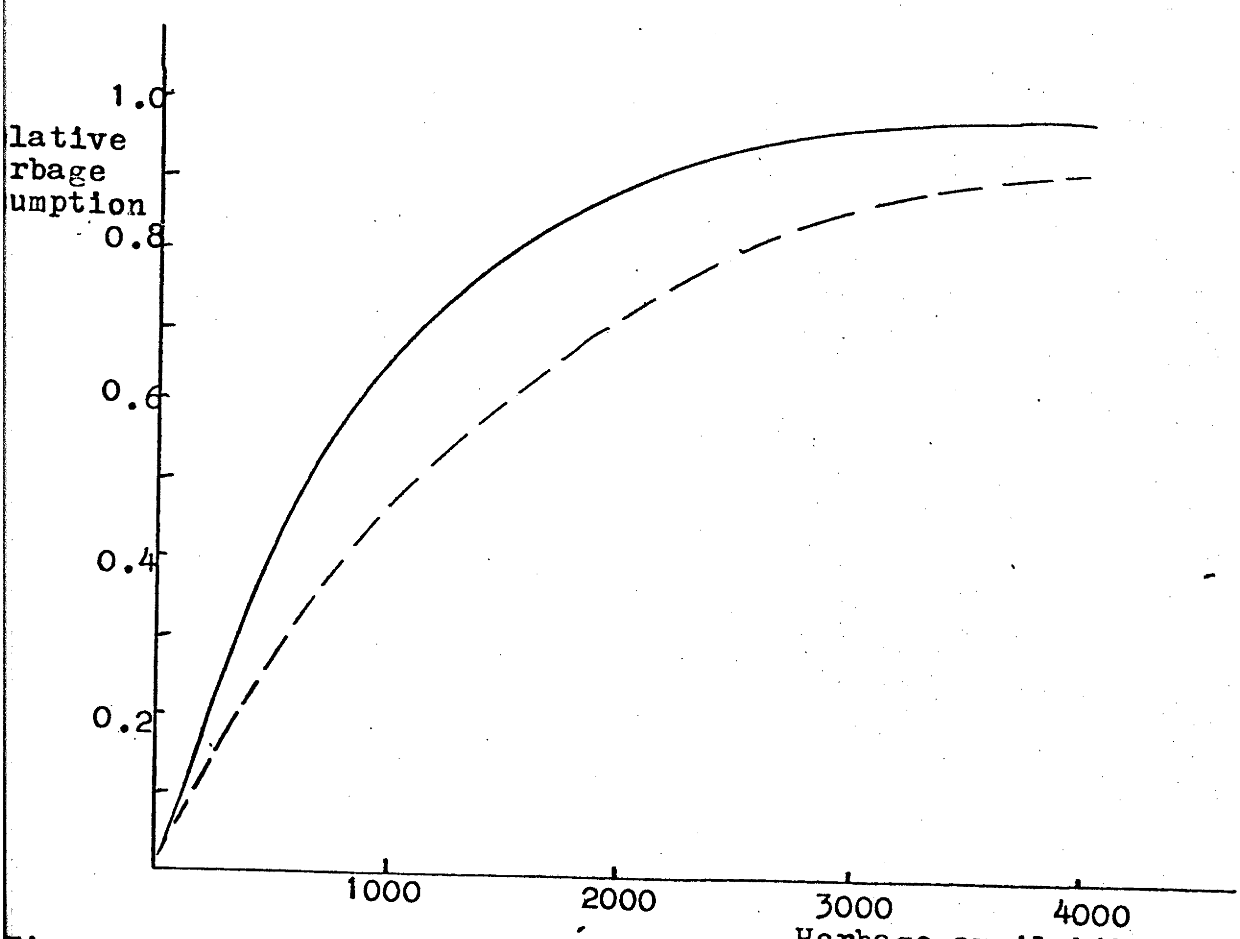


Figure 5.10:Relationship between relative herbage consumption and availability for the green(—)and dead(---) fractions.

pasture consumption by sheep. The concept is now generally accepted that a greater amount of herbage on offer will lead to higher intake levels, as a result of the greater ease with which plants may be prehended by the grazing animal. This relationship reaches an asymptote at a particular weight of herbage but the level has proved difficult to determine, due to the interaction of a number of characteristics of the pasture (yield and height of sward) and of the animal (rate of biting, size of bite, total grazing time). Reported figures of the asymptotic value of availability range between 700 and 2500 kg ha^{-1} (Arnold and Dudzinski 1967, Willoughby 1959, Arnold 1964, McKinney *et al.* 1970).

A different approach was proposed by Allden and Whittaker (1970). From observations on rates of intake and grazing time at varying availabilities and leaf lengths, they concluded that leaf length had the more important effect on intake. However, this conclusion should be treated with caution, as sheep were subjected to a fasting period before entering low availability plots, in order to get them to graze, and secondly, the different levels of availability were achieved by alternating strips of pasture and cultivated land of differing widths, points which detract from the realism of the situation. Arnold and Dudzinski (1967) reported that in one year herbage availability was more closely correlated with intake than was leaf length, but in the following year the reverse applied.

It is possible that the true nature of the relationship is represented by a combination of both these factors, weight of herbage per unit area and plant height. There is, however, little information available to support this theoretical approach and most modellers of grazing systems have chosen functions that describe the effect of availability on intake solely on the basis of the amount of herbage on offer (Freer *et al.* 1970, McKinney 1972, Vickery and Hedges 1972).

In this model, feed intake was assumed to increased with increasing availability towards an asymptote. The dry matter yields at which 90 *per cent* of potential intake occurs, are 2000 and 3500 kg ha^{-1} for the green and dead herbage fractions respectively. The exponential equation selected was developed by F.H.W. Morley (personal communication) and is illustrated in Fig. 5.10.

APIA = 1.0 - EXP(-A*D/700.0) (3)

where APIA = actual intake as a proportion of potential intake

A = herbage availability (kg DM ha^{-1})

D = herbage digestibility

(b) Diet composition in relation to feed supply

Herbage on offer to the grazing animal is divided into two classes: green and dry (or dead). The green herbage pool is composed of the growing material and this is assumed to have a homogenous composition. Each week some of the uneaten green herbage is transferred to the dead herbage pool and some of the dead material disappears by decay.

From these two classes of herbage, the animal is assumed to prefer green material and the amount of green eaten, GEPH (kg $head^{-1}$ day^{-1}), is calculated from the following equation:

GEPH = U*APID*APIA

where U, APID and APIA are the parameters calculated in equations (1), (2) and (3) above. The potential intake of dry herbage, PDE, is then calculated as follows:

PDE = U - GEPH

and the actual intake of dry material, DEPH (kg $head^{-1}day^{-1}$), is calculated from its availability and digestibility

DEPH = PDE*APIDD*APIAD

where APIDD and APIAD are the corresponding factors for dry herbage and are also calculated from equations similar to nos. (2) and (3) above.

It follows that when ample green herbage is available, little dry material is eaten; but as the availability of green material falls, the animals will be forced to eat more dry material. However, even if there is ample dry herbage, total intake will then be lower because of its poorer digestibility.

The digestibilities of the green and dry fractions of the forage are considered in this model to be constant throughout the year. In fact, it must be recognized that within a pasture or crop canopy there are different components (leaves, sheaths, stems) having distinct nutritive values for the grazing animal. Moreover, there are quality changes within these components, due to plant aging. The model could be further improved to account for these changes in herbage digestibility with age, provided that the relationship for the forage concerned is known. This approach has been used in the models developed by Freer *et al.* (1970) and Rice *et al.* (1974).

(c) Utilization of dietary energy

The gross energy consumed by the animals undergoes digestion and absorption in the gut and the resulting metabolizable energy is used to satisfy the energy requirements for maintenance and production.

The energy partition system adopted here mainly follows that outlined in A.R.C. (1965).

The total content of digestible dry matter of the diet, DFUE, is calculated as the sum of the products of green and dry herbage dry matter consumed, GE and DE (kg ha^{-1}), and their corresponding digestibilities, DG and DD, as shown in the function below.

DFUE = GE*DG + DE*DD

Digestible energy intake, DEI, is estimated on the basis of 4.0 kcal g^{-1} of digestible dry matter (Blaxter 1967), i.e.

DEI = DFUE*4000

Metabolizable energy (ME) is calculated as 82 *per cent* of digestible energy (Blaxter, 1964).

The energy requirements for maintenance are first subtracted from the total amount of ME consumed. If there is a surplus remaining, this is used by the animal for productive purposes. Determinations of the energy expenditure (heat production) of animals kept at a constant body weight have provided estimates of maintenance requirements (see A.R.C. 1965). However, these estimates have been made mainly on housed animals and cannot be applied to grazing situations. Measurements of the energy expenditure of grazing sheep have shown a considerable variation, ranging from values only slightly greater than those for comparable animals kept indoors (Langlands *et al.* 1963) to some values that are up to three times as great (Lambourne and Reardon 1963, Arnold *et al.* 1965).

Fasting metabolism (M) of both cattle and sheep has been found to be exponentially related to liveweight (W) i.e. $M = aW^b$, where a and b are constants, with b = 0.75. Results obtained with animals of different ages have also shown a decline in fasting heat production per unit metabolic live weight ($W^{0.75}$) with increasing age (Ritzman and Benedict 1931, Blaxter 1962). Given that the simulated flock is composed only of adult sheep, the effect of age has not been considered in this model.

The efficiency of utilization of ME for maintenance (k_m) varies little over a wide range of farm feeds. Blaxter (1967) reported that k_m could be predicted from the ratio of ME to gross energy of the diet (Q_m) by the function:

$$k_m = 54.6 + 0.30\ Q_m$$

so that the likely range of k_m is only 73-77 (A.R.C. 1965). Assuming therefore that k_m is constant, the metabolizable energy requirement for maintenance, EMR (kcal day^{-1}), is calculated from a formula recently reported by Young and Corbett (1972).

EMR = 132*W**0.75

Predicted values from this equation are 60-70 *per cent* greater than those for housed sheep and the experimental conditions indicate that the formula would be applicable only to adult sheep weighing more than 25 kg.

Energy retention in the body occurs if the energy balance, EB, after subtracting maintenance, is positive. The utilization of ME for the synthesis of body tissue is less efficient than for maintenance and more dependent on the quality of the diet. Using the function developed by Blaxter (1967), energy above maintenance requirements is retained with an efficiency, VMEP, which depends on the ME concentration of the diet, PMEF, in the following way.

VMEP = 0.81*PMEF + 0.03

where PMEF = 0.81*DFUE/(GEPH + DEPH)

The product of ME surplus to maintenance and the efficiency factor VMEP gives the net energy content of new body tissue. The resulting weight change can be calculated if the energy content of weight change (ECWT) is known. Vickery and Hedges (1972) calculated from published data an equation for sheep which shows that ECWT (Mcal kg^{-1}) increases linearly with liveweight, W. Their equation applies only to sheep over 20 kg as there is a curvilinear relationship at lower weights (Fig. 5.11).

ECWT = (W - 20.0)* 0.143 + 2.72

Hence, when EB is positive, the increase in body weight, CLWCH (kg day^{-1}) is calculated as:

CLWCH = VMEP*EB/ECWT*1000

When EB is negative, the energy deficiency is met by catabolism of body tissue . The efficiency of utilization of these reserves for maintenance, VMEM, is set at 0.83, and the resulting weight loss, CLWCH (kg day^{-1}) is now estimated as:

CLWCH = EB/ECWC*1000*VMEM

(d) Wool production

Wool growth in sheep is a process that continues regardless of its energy needs being met by dietary energy or by energy stored in body tissue. In his model, White (1975) assumed that wool production at zero intake does not cease but merely falls to 20 *per cent* of its potential. Blaxter (1967) and Spedding (1968) have reported the growth of wool at intake levels below maintenance. On the other hand, the rate of wool growth is certainly related to the level of intake (Ferguson 1962, Spedding 1968). White (1975) assumed that

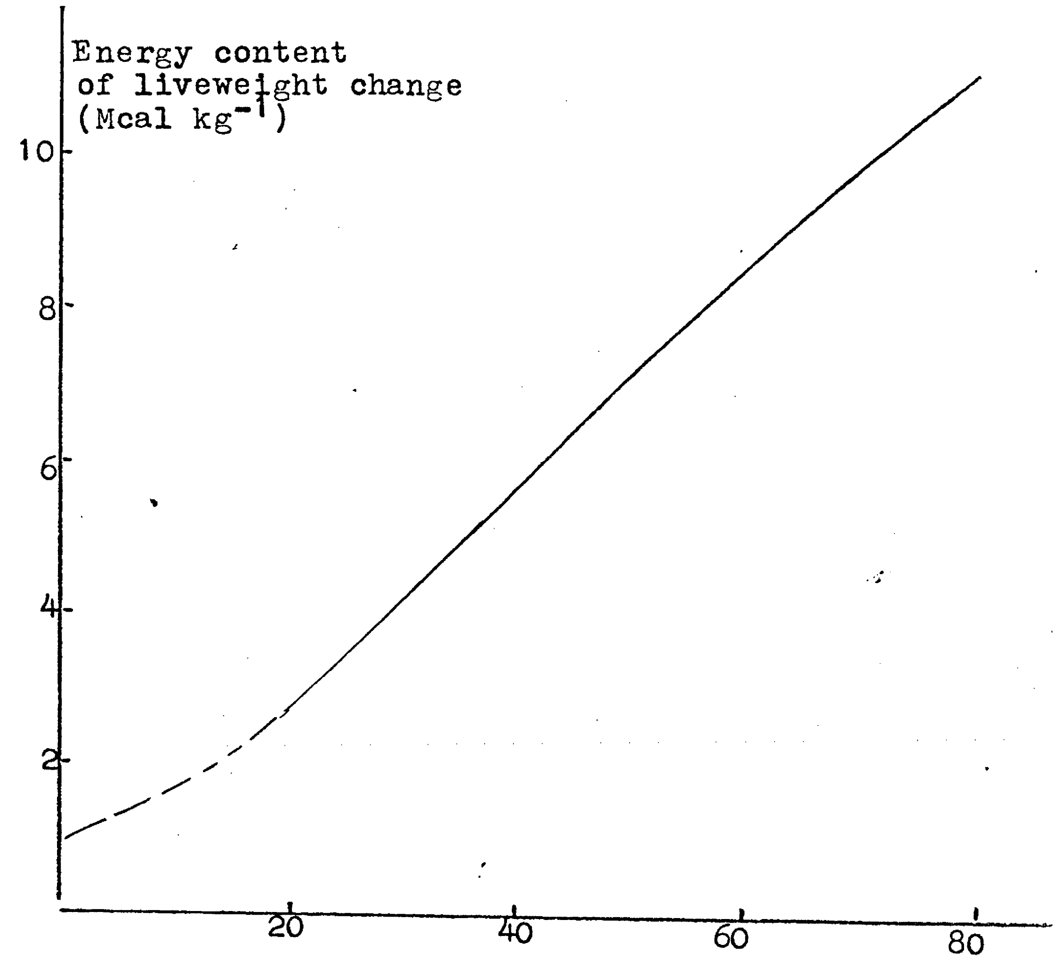


Figure 5.11: Energy content of liveweight change as a function of fleece free liveweight (From Vickery and Hedges, 1972)

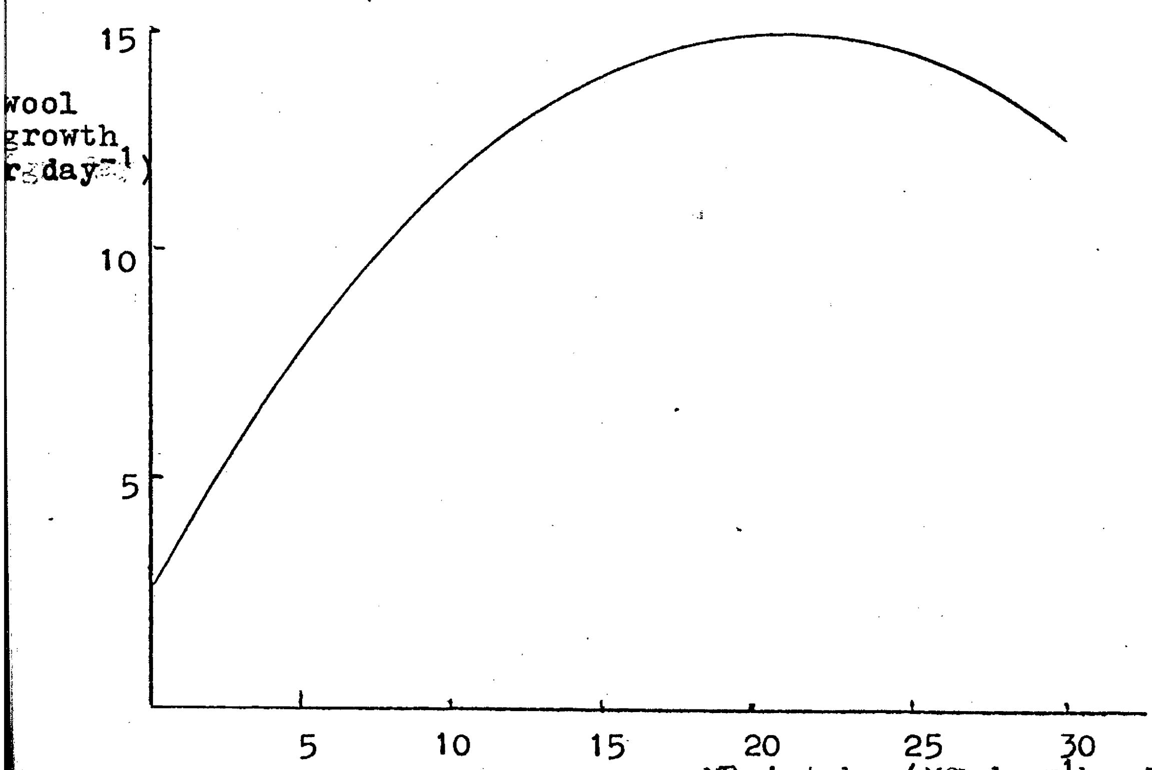


Figure 5.12: Relationship between wool growth rate (gr day^{-1}) and ME intake (MJ day^{-1}head^{-1}).

wool production is linearly related to the intake of metabolizable energy. If this were so, then the efficiency of wool production would remain constant as intake level increases. However, experimental measurements by Ferguson (1962) have shown that efficiency decreases with increasing feed intake and this is supported by Blaxter (1968).

If wool growth rate, WULDAY (kg day^{-1}) is assumed to be curvilinearly related to ME intake, WMEI (Mcal day^{-1}), then the relationship can be adequately expressed by the following equation, which is similar to that used by Christian *et al.* (1976) (Figure 5.12).

$$WULDAY = 0.003 + 0.001*WMEI\ (5.02 - 0.518*WMEI)$$

The maximum daily wool growth estimated by this equation is 0.015 kg day^{-1}. The constant 0.003 represents wool production at zero intake (20 *per cent* of maximum production).

(e) Economic value of lamb production

A non-conventional approach was used in this model to simulate the effect of different grazing management policies on meat production from lambs. For simplicity, the mating, pregnancy and lactation cycle of the ewew was not simulated. Instead, the production of prime lamb from the grazing system was predicted from the weight pattern followed by the ewe during the relevant period of the year. The basis of this approach lies in the strong overall relationship between the weight or body condition of the ewe and the weight of marketable lambs (Curll *et al.* 1975). The economic value of lamb production was therefore predicted by applying a differential evaluation to ewe liveweight at different times of the year, according to its expected contribution to the final product.

Firstly, an optimum ewe liveweight, OPTWT, was selected for each week of the year (Fig. 5.13) in relation to the physiological stage of the ewe (dry, mating, pregnant or lactating). It was then assumed that when actual ewe weight, ACTWT, fell below the optimum, the potential contribution of that week to the value of the prime lamb would be reduced proportionally, according to the following equation:

$$WTF = (ACTWT - 35.0)/(OPTWT - 35.0)$$

where WTF ($0<WTF<1$) is the factor to be applied to the value of lamb for the particular week. The weight 35 kg is set as a lower limit because mortality from undernutrition can be expected to start at this point (Arnold *et al.* 1971).

Secondly, a financial value is set on the importance of ewe liveweight during each week of the year, with respect to its contribution to prime lamb output. With prevailing market conditions, the average value for each week would be 15¢ but, quite clearly, liveweight during mating or lactation is of more importance than during early pregnancy. The maximum value of lamb attainable, VALWT, for each week of the year ranges, therefore, from \$0.04 when the ewes are dry to \$0.25 during lactation. The actual value of lamb, VALAMB (\$), for each week is then calculated as:

$$VALAMB = WTF*VALWT$$

(f) Mortality rate in relation to liveweight

As mentioned above, it is assumed that deaths from undernutrition start to occur when liveweight falls to 35 kg. The death rate then increases rapidly with falling mean weight until, at 25 kg, it is assumed that all the animals will die.

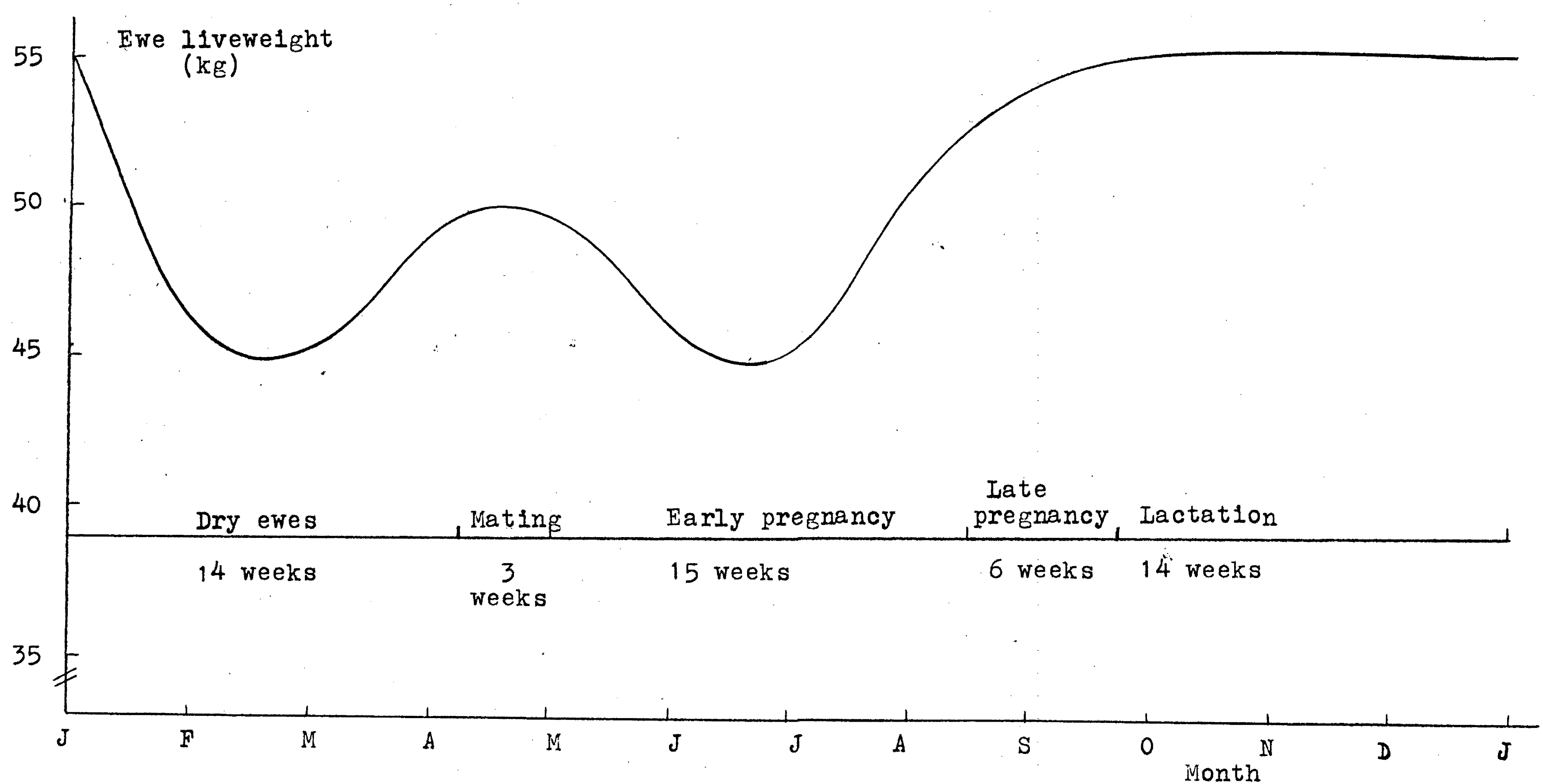


Figure 5.13: Estimates of the optimum liveweight of the ewe in relation to its physiological stage.

The relationship between mortality rate, CDTH (0<CDTH<1), and liveweight, W (kg), is described by the following equation:

$$CDTH = EXP(-0.45*(W - 25.0))$$

If mortality occurs, the mean liveweight of the remaining sheep is adjusted, on the assumption that those which die weigh 5 kg less than the mean weight of the flock.

CHAPTER 6:

I. VALIDATION OF THE PASTURE SUBMODEL

II. USE OF THE MODEL FOR A MANAGEMENT-ORIENTED SIMULATION EXPERIMENT

I. *VALIDATION OF THE PASTURE SUBMODEL*

In the field of agricultural science, as well as in many others, there is always the problem of relating experimental results to the real system, because the experimental environment usually differs from that in which the results are to be applied. Simulation modelling of biological systems is no exception to this rule, with the disadvantage that the modeller's experimental plot (the model) bears little physical resemblance to reality. The use of a model to solve practical problems implies making inferences about reality which require some evaluation of how well the model represents the real system.

The process of evaluating the model in relation to reality is referred to as the verification or validation stage of simulation. Simulation being a human activity that has developed only recently, it is not surprising that conflicting opinions are held on the 'best' procedures to use. This is particularly true of validation which represents one of the major unsolved problems of simulation (Wright 1970).

Verification and validation are terms which refer to different processes in relation to simulation studies. Verification of the model is concerned with establishing whether the model is a true or correct representation of reality. On the other hand, validation is not so much concerned with the correctness of a model, but rather whether it is effective or suitable for a specific purpose. Thus, a model is validated in relation to the purpose for which it was constructed, whereas a model is verified in relation to absolute truth (Wright 1971).

Some of the techniques proposed for verification and validation (Naylor and Finger 1967, Hermann 1967) suggest that the distinction is semantic rather than real, since both processes are part of a multi-step procedure in which the ultimate objective is to assess model validity. Hence, in the following paragraphs, the term validation will be used in a general sense to describe the total process of comparing model output with observed results.

There are a number of methodological approaches to validation which have been discussed in detail by Wright (1970). From these and other studies (Wright and Dent 1969, Anderson 1974) it is obvious that validation always involves a considerable degree of subjectivity. If the real system does not exist, then the only alternative to validation is subjective judgement of model output. However, if the model has been constructed to analyse a specific problem of a real system, then there exists the possibility of making some comparisons with reality.

The first problem is deciding what aspects of system performance should be compared. This must be considered in relation to whether the available data permit the evaluation of total system output or only some system parts.

In the present model, the lack of data on the behaviour of the system as a whole severely restricted any ambitious validation plans. The information most readily available was that pertaining to pasture growth rates, provided by the experiment described in Chapter 3. These data were considered to represent potential pasture growth rate, so that a comparison was made with predicted values of this variable as derived from the equation for GRMAX in Chapter 5. Model output was generated for the years 1974 and 1975 under identical climatic conditions to those prevailing in the experiment. The weights of green and dry pasture in week 1 of the simulation (initial values) were calculated as the mean of ten model runs using a historical series of climatic data.

The second problem is deciding the basis for comparison. This is probably not very relevant to variables that can be measured only at isolated points in time, e.g. wool growth. The real problem arises when the variables are in the form of a time series, such as pasture yield or animal weights. Cyert (1966) has suggested a methodology for comparing time paths on the basis of the following measures:

(1) number of turning points,

(2) timing of turning points,

(3) direction of turning points,

(4) amplitude of the fluctuations for corresponding time segments,

(5) average amplitude over the whole series,

(6) simultaneity of turning points for different variables,

(7) average values of variables, and

(8) exact matching of values of variables.

Each of these measures refers to some specific aspect of the agreement or disagreement between observed and predicted values. There is, however, no basis for choosing which, if any, of these measures are the most suitable.

Graphical comparisons of predicted and observed values of growth rates for two levels of stocking rate are presented in Figures 6.1 and 6.2. Some of the inconsistencies in the matching of values of variables could be accounted for by inherent features of the sets of data being compared. Experimental measurements are usually characterized by a considerable degree of variability which, if unlikely to conceal the general trend of a time series, may show fluctuations which are difficult to interpret. On the other hand, simulated results, particularly if derived from deterministic models such as this, will invariably show a high degree of smoothing. This arises from the fact that the transformation of input into output is carried out by means of adjusted relationships. For example, the figures of average amplitude over the whole time series presented in Table 6.1 show a considerable difference between observed and predicted values, whereas

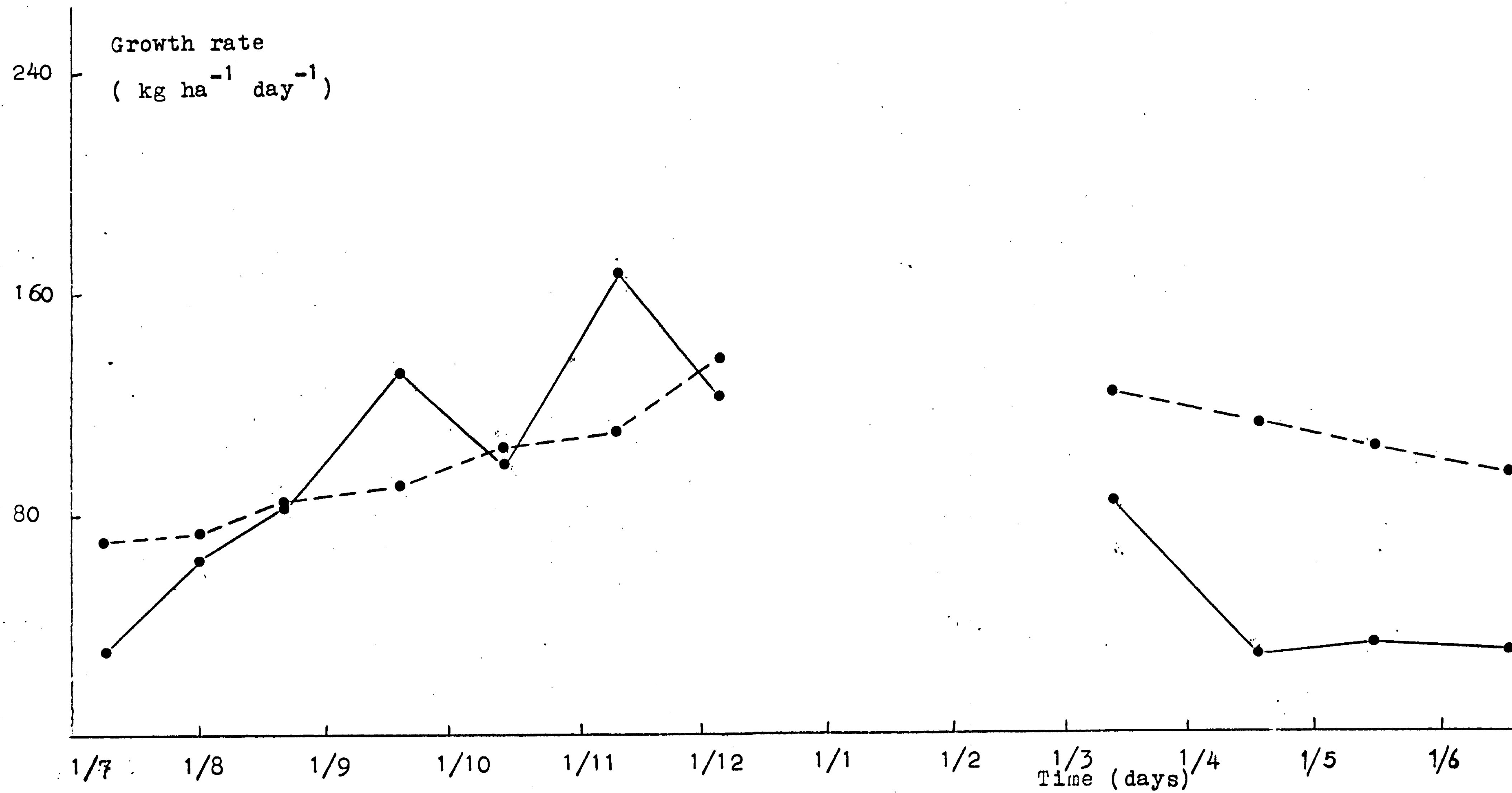


Figure 6.1: A comparison of model output (●---●) and observed values (●——●) for the 7 sheep per hectare treatment. Predicted values are for above-ground growth and observed values are for total growth.

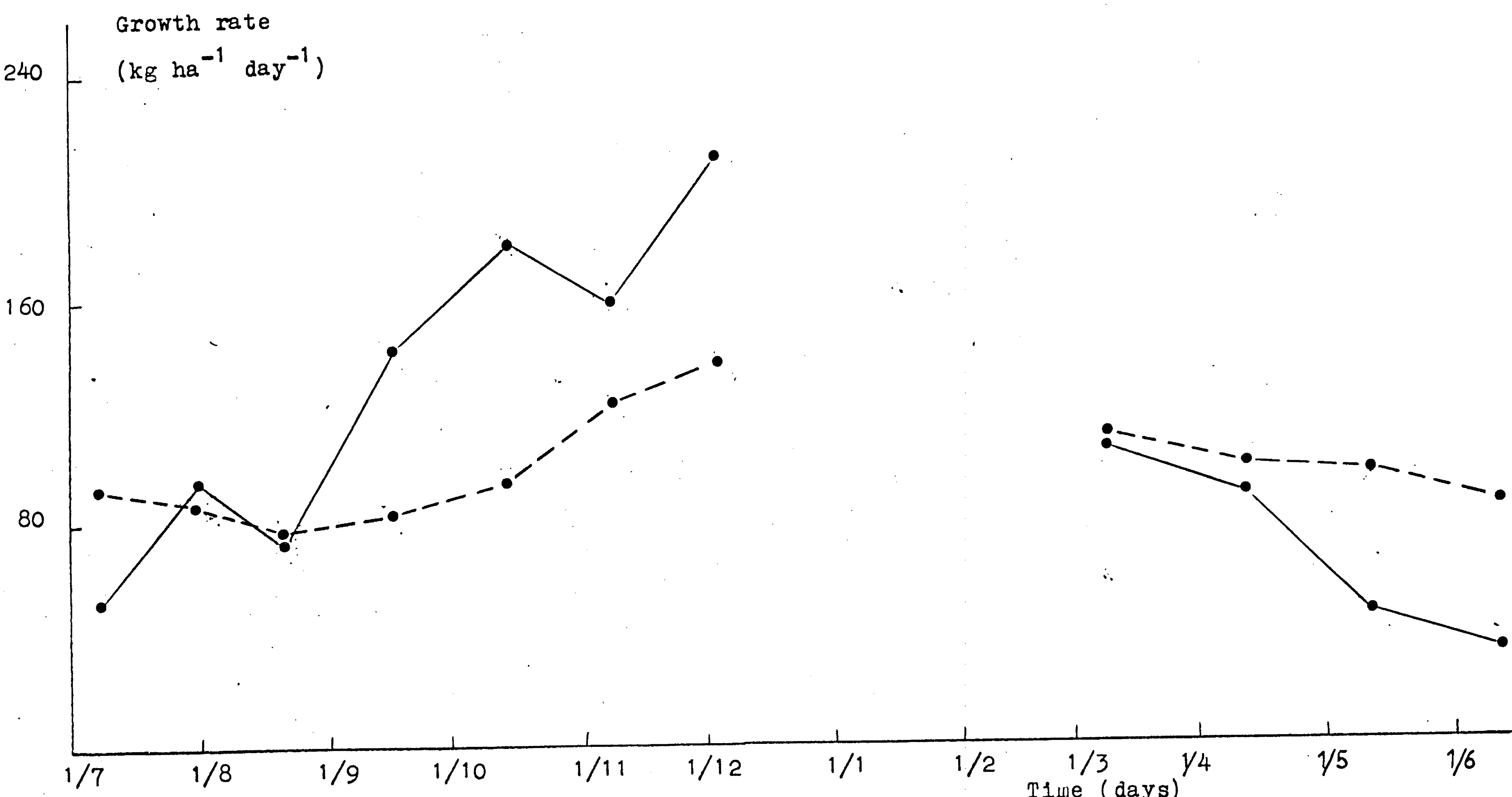


Figure 6.2: A comparison of model output (●---●) and observed values (●——●) for the 30 sheep per hectare treatment. Predicted values are for above-ground growth and observed values are for total growth.

the figures of average values of variables are of similar magnitude.

TABLE 6.1: Values of Cyert's measures for predicted and observed growth rates of pastures grazed at different stocking rates.

Measure	7 sheep ha^{-1} Observed	7 sheep ha^{-1} Predicted	30 sheep ha^{-1} Observed	30 sheep ha^{-1} Predicted
Number of turning points	3	1	5	2
Timing of turning points				
1	16 Sept.	11 Mar.	31 Jul.	20 Aug.
2	12 Oct.		20 Aug.	9 Mar.
3	8 Nov.		12 Oct.	
4			6 Nov.	
5			9 Mar.	
Amplitude of the fluctuations for the corresponding time segments*				
Winter	53.3	10.5	44.7	16.8
Spring-early summer	71.4	45.6	68.6	54.7
Autumn	55.4	29.2	74.3	25.9
Average amplitude over the whole series*	137.8	65.5	179.4	59.4
Average values of variables*	82.0	101.4	107.4	98.2

* Values expressed in kg DM ha^{-1} day^{-1}

An examination of corresponding time segments in Figures 6.1 and 6.2 indicates that the agreement between the model and experimental results is short of being perfect. A consistent overestimation of growth rates was observed in winter and autumn, i.e. when herbage yields were low, contrasting with an underestimation during periods of higher herbage yields (spring-early summer). These differences could be narrowed by modifying the Richard's growth function used in the model to predict maximum pasture growth rates (Figure 5.3, Chapter 5). Increasing the value of the parameter m would result in decreased growth rates at low herbage yields and vice versa. This way the pasture submodel could be 'tuned' to generate results which would agree more closely with the observed values.

One might wonder, however, whether the experimental data are of such an excellence as to warrant modifications to the model. In my opinion, and with particular regard to this case, such modifications could be justified if a second set of data was available to test the modified model. If the two sets of data showed consistent results and the second comparison of the model showed closer agreement between observed and predicted values, then there would be some grounds to assert that the predicting capacity of the model was improved. But if changes to the model were decided on the basis of a single testing, there would exist the risk of transforming simulation into a curve-fitting technique.

A related problem is that the objective of the study should be kept in mind when deciding on the severity of verification/validation procedures. As Wright and Dent (1969) have noted, if the objective is to investigate the structure of the actual system (systems analysis), then fairly rigorous verification of both the components and the model as a whole will be required to prove or disprove hypotheses with any degree of accuracy. But if simulation is used for system synthesis, i.e. to solve a management problem in terms of specifying a set of decision rules to achieve some objective, then there is little point in insisting that the model should predict to a given degree of accuracy, if this accuracy cannot be incorporated into the management decision. For example, it may not be necessary for a management model to predict exactly the grain yield to be obtained from, say a given amount of herbage at the end of grazing since the farmer cannot be expected to estimate accurately such an amount and so know when to stop grazing.

The experiment concerned with net primary production of pastures (Chapter 3) provided no data against which to validate the model as a whole. In the absence of actual data the considerations of Dann *et al.* (1974) could serve as a basis for comparison. They estimated that the gross margin per hectare on an all-pasture system at 12 ewes per hectare would be at least \$150, assuming costs and product prices similar to those used in the simulation experiment reported in Section II of this Chapter. Mean net return per hectare predicted by the model for the same type of system at 15 ewes per hectare (Table 6.4b) was \$149.3. Although a comparison such as this is not meant to be conclusive, the concordance is encouraging and some confidence can be placed on the overall ability of the model to predict.

II. USE OF THE MODEL FOR A MANAGEMENT-ORIENTED SIMULATION EXPERIMENT

The main purpose of a simulation study can vary widely, from gaining a thorough understanding of the structural and functional aspects of the system, attempting to detect potential research areas and teaching, to studying a specific problem such as the evaluation of a farm management practice. In this last case, physical experimentation is unlikely to be a viable tool in view of the time and cost involved in experimenting with real systems. Experiments with grazing systems, for example, require a considerable investment in land, capital and labour. Climatic variability necessitates replication over time to accumulate sufficient results for meaningful analysis, and replication over space may be necessary if inferences are to be made beyond the particular locality of the experiment.

From the point of view of the simulation study itself, the phase of experimentation is likely to prove most useful to the modeller since it will (i) provide him with feedback information about the simulated system, and (ii) enable him to assess the behaviour of the entire model on the basis of whether or not the varying experimental conditions result in logical system responses.

The objective of experimentation with simulation models in management-oriented studies will usually be one of the following (Wright 1970):

(i) to compare alternative courses of action,

(ii) to estimate the response of the system to changes in the level of a single input,

(iii) to explore the response surface generated for different combinations of input levels, or

(iv) to estimate the input combination required for an optimal or near-optimal level of output.

With the objective of exploring a response surface, the model of a mixed sheep-cropping system described in Chapter 5 was used to conduct a simulation experiment including a range of cropping levels and stocking rates.

The simulation experiment

In areas where low winter temperatures limit forage production from pastures, the use of fodder crops has become a common practice. These offer the possibility of filling the winter feed gap, with the added advantage that some extra benefit can be obtained by harvesting the grain. Evaluation of dual purpose crops requires comparisons among at least three systems (Morley 1968): (i) grazing pastures without fodder crops, (ii) grazing with a portion of the area sown to fodder crops, and (iii) grazing combined with grain production from a portion of the farm which is not grazed during the growing season, including the periods of fallow and preparation.

The design of the simulation experiment reported here followed these guide-lines for a range of three sheep stocking rates with an oats crop .

For systems (ii) and (iii) varying proportions of the farm were under crop and for system (ii) different policies for crop grazing management were included. A thorough exploration of the response surface involving several levels of each variable would have required a full factorial approach. The impracticability of this, given the amount of computing time that would have been needed, called for the use of a more efficient experimental design. However, as Burdick and Naylor (1966) have noted, it may be difficult to identify the best experimental design for general exploration because the goal is somewhat imprecise. The main objective therefore was the exploration of an optimal region rather than the precise definition of the optimal point.

The pasture and dual-purpose crop system was simulated over three stocking rates on the farm, with three proportions of the farm sown to crop, two proportions of the stock grazing on the crop and two intensities of crop grazing; 36 treatments in all. The pasture and ungrazed grain crop (system iii) included the same three proportions sown to crop and the same three stocking rates. These, combined with the pasture only system run at three stocking rates, gave an additional 12 treatments, making a total of 48 treatments. Each treatment was replicated ten times for the same 10-year sequence of climatic data. The resulting 480 runs required 560 minutes of computing time on an IBM 360 computer. A diagram of the incomplete factorial design used for the experiment is shown in Table 6.2. In this table SR stands for stocking rate on the farm (sheep ha^{-1}), FRAC represents the proportion of the farm sown to a dual-purpose oat crops, FRACS represents the proportion of the sheep grazing the crop and LEVCRP denotes the intensity of crop grazing. Levels 2 and 4 indicate that grazing will end when the weight of crop herbage falls below 1250 or 250 kg green DM ha^{-1} respectively.

The results from the experiment described in Chapter 4 were used to estimate the effect of the intensity of grazing on grain yield. The curvilinear regressions (1) and (2) shown in Table 4.6 (Chapter 4) suggest that either of the independent variables can be used as a good single predictor for grain yield. However, if only green dry matter at the end of grazing is used as the predictor, the effect of climate on crop growth between the end of grazing and flowering would not be taken into account. On the other hand, if green dry matter at flowering is the predictor, then the independent effect of herbage remaining after grazing, as discussed in Chapter 4, would be underestimated. Hence, in the final version of the model, grain yield (GY) in kg ha^{-1} was predicted from the following multiple linear regression equation:

$$GY = 399.93 + 0.1792*FINLAV + 0.1959*FLOWYL \quad (r^2 = 0.76)$$

where FINLAV and FLOWYL represent weights of green dry matter (kg ha^{-1}) at the end of grazing and at flowering respectively.

The experiment was set up to represent a 2000 ha farm situated in the same area where both the field experiments presented in Chapters 3 and 4 were conducted. The area to be cropped was withdrawn from grazing in week 1 (i.e. in the first week of March) and was sown to oats in week 3. The decision on when to commence grazing the crop was based on the weight of green herbage dry matter, to ensure that the plants were sufficiently well rooted to withstand grazing. This weight was assumed to be 1250 kg ha^{-1} (Crofts 1966). Crop grazing ended either in the week when the crop had been grazed down to the level fixed by LEVCRP or, at the latest, week 30. The latter time corresponded to the last week in August, i.e. 14 weeks before the time set for harvest. The experimental results from the longest period of crop grazing (Chapter 4), which also extended to 14 weeks before harvest, suggest that a significant reduction in grain yield can be expected if

TABLE 6.2: Values selected for the management variables used in the simulation experiment

SR	FRAC	FRACS	LEVCRP
7.5	0	0	0
	0.1	0	0
		0.1	2
			4
		0.3	2
			4
	0.3	0	0
		0.3	2
			4
		0.5	2
			4
	0.5	0	0
		0.5	2
			4
		0.7	2
			4
15.0	*idem*	*idem*	*idem*
22.5	*idem*	*idem*	*idem*

grazing is continued any longer. However, as there were no data to develop a quantitative relationship beyond this point, crop grazing in the simulation experiment was ended at a time when length of grazing in itself was most unlikely to affect grain yield. After harvest, the stubble was not grazed but allowed to lie in fallow for the next year's crop.

The comparison between management policies was based on the values for mean net returns (\$ ha^{-1}) calculated as gross production minus variable costs. Gross production per hectare was calculated as the sum of returns from wool, lambs and grain. Costs per hectare were calculated by adding the costs of cropping, including cultivation, seed, fertilizer and harvest to the variable costs of the flock including labour and shearing, the costs of sheep replacement on the basis of a 20 *per cent* annual culling rate and the cost of replacing ewes that died, so that the flock was restored to its original size at the start of each year.

Analysis of the response surface

The results presented in Table 6.3 show that system response was relatively insensitive to changes in the levels of FRACS or LEVCRP, although there was a slight trend to decreasing returns with increasing values of these variables. However, as will be seen later, these were only minor changes compared with those observed at different stocking rates. This conclusion does not necessarily indicate that stocking rate on the crop or the intensity of crop grazing are unimportant, but possibly that the model may not be sufficiently realistic for this purpose. Hence, for comparisons of the mean net returns from different levels of cropping, the four values corresponding to the two levels of FRACS and the two of LEVCRP were averaged.

The resulting values are shown in Tables 6.4 a, b and c for 7.5, 15.0 and 22.5 sheep ha^{-1} respectively. At 7.5 sheep ha^{-1}, for the pasture and ungrazed crop system, economic returns increased with increasing level of cropping. However, at 15.0 sheep ha^{-1}, this trend was reversed, clearly demonstrating the sensitivity of the system to changes in stocking rate. In both cases, there was a constant increase in the coefficient of variation as cropping level increased. The results for the highest stocking rate are presented here only for illustrative purposes since, under these conditions, all but one of the systems operated at a loss.

The above results indicate that the optimal region is bounded by 0 and 10 *per cent* cropping and by 7.5 and 15.0 sheep ha^{-1}. Within this area the

TABLE 6.3: Mean net returns and coefficients of variation at 7.5 sheep ha^{-1} for varying levels of FRAC, FRACS and LEVCRP

FRAC	FRACS	LEVCRP	Mean net returns ($\$$ ha^{-1})	Coefficient of variation (%)
0	0	0	103	26.1
0.1	0	0	107	34.4
	0.1	2	104	34.2
		4	103	34.2
	0.3	2	105	34.4
		4	98	34.2
0.3	0	0	111	63.7
	0.1	2	105	64.9
		4	104	65.1
	0.3	2	103	65.0
		4	100	66.2
0.5	0	0	113	85.4
	0.1	2	106	86.7
		4	105	87.1
	0.3	2	103	87.6
		4	101	88.9

TABLE 6.4: Production, costs and net returns (\$ ha^{-1}) for different combinations of input variables

(a) - Stocking rate = 7.5 sheep ha^{-1}

FRAC	FRACS	Production from Wool	Production from Lambs	Production from Grain	Cropping	Costs Variable + Replacement	Mortality	Mean net returns (\$ ha^{-1})	Coefficient of variation (%)
0	0	86	55	0	0	37	1	103.0	26.1
0.1	0	85	55	12	4	37	3	107.0	34.4
	CG*	85	55	8	4	37	3	102.4	34.2
0.3	0	82	54	36	13	37	11	111.1	63.7
	CG	82	54	28	13	37	11	103.1	65.1
0.5	0	77	50	59	22	36	17	112.5	85.4
	CG	78	51	49	22	36	17	103.9	87.6

TABLE 6.4: Continued

(b) - Stocking rate = 15.0 sheep ha^{-1}

FRAC	FRACS	Production from Wool	Production from Lambs	Production from Grain	Cropping	Costs Variation + Replacement	Mortality	Mean net returns ($ ha^{-1})	Coefficient of variation (%)
0	0	155	101	0	0	72	35	149.3	125.4
0.1	0	151	96	12	4	72	39	143.0	134.2
	CG	151	96	8	4	72	39	139.5	136.3
0.3	0	134	63	36	13	70	68	82.4	245.9
	CG	138	71	24	13	70	53	97.3	195.7
0.5	0	76	31	60	22	59	197	-110.1	225.0
	CG	112	50	42	22	63	140	- 31.5	1474.3

TABLE 6.4: Continued

(c) - Stocking rate = 22.5 sheep ha^{-1}

FRAC	FRACS	Production from Wool	Production from Lambs	Production from Grain	Cropping	Costs Variation + Replacement	Mortality	Mean net returns ($ ha^{-1})	Coefficient of variation (%)
0	0	193	87	0	0	104	135	41.7	767.9
0.1	0	160	71	12	4	98	221	-134.4	241.3
	CG	170	74	8	4	99	191	- 42.9	1003.5
0.3	0	96	32	36	13	84	360	-293.1	107.5
	CG	117	48	25	13	88	295	-206.9	180.0
0.5	0	11	3	60	22	66	534	-548.4	12.3
	CG	60	12	42	22	76	471	-455.8	38.5

* CG stands for 'crop grazed'.

greatest contribution to gross production is made by the returns from wool, followed by those from the sale of lambs, with the highest costs being labour and the replacement of ewes.

As the 15 sheep ha^{-1} boundary is approached, mean net returns increase by up to 45 *per cent* (for FRAC = 0), with a concurrent rise in the coefficient of variation from 26.1 to 125.4. The higher profitability is caused by increased returns from wool and lambs which more than compensate for the higher costs of labour, replacement and mortality. It is in fact the latter which largely determines the changes in the coefficient of variation, because of the high mortality in unfavourable years. The decision on whether to run the farm with lower profits and less risk or higher profits but greater risk will depend on the decicion-maker himself.

Changing the level of cropping from 0 to 10 *per cent* of the farm appears to be a less attractive proposition, since little improvement in net returns can be expected and the coefficient of variation is likely to increase - by 31 *per cent* at the lowest stocking rate. In this case the extra benefit from the sale of grain is almost offset by the cost of cropping and the increased mortality. Only in one case did crop grazing result in increased system productivity and this was at 15.0 sheep ha^{-1} with 30 *per cent* cropping. This was the result of higher production of wool and lambs and lower mortality which more than offset the reduction in the marginal return from grain.

It can thus be concluded that the optimum system was 15 sheep ha^{-1} with no cropping, while the most stable policy was 7.5 sheep ha^{-1} with up to 10 *per cent* cropping. Even when small benefits could be obtained from higher proportions of crop for grain only, the increased unreliability of the system output casts some doubts on the advantage of such a practice. Axelsen *et al.* (1970) arrived at a similar conclusion after three years of experiments with sheep and grain production systems using pasture and oats. They suggested that one-third of the area for cropping might be too high a proportion in view of the penalty imposed on other farm products by overstocking the uncropped area. Furthermore, their results did not indicate marginal profits necessary to justify the outlay on the cropped area of the farm. In a simulation experiment conducted by Wright (1970) the trend was clearly one of decreasing returns per acre as the proportion of the farm in crop was increased. Results from some other field experiments with grazing oats and pasture have shown that fodder cropping has little to offer in terms of annual production of wool and lambs (Dann *et al.* 1974) or beef from weaners (Hennessy and Robinson 1975).

It must be borne in mind that the evaluation of management policies in the present simulation experiment was made on the basis of only one relationship between prices of products. A more comprehensive study would be necessary to assess the benefits attainable from such policies for varying price structures.

CHAPTER 7:

GENERAL DISCUSSION AND CONCLUSIONS

Learning about the structure and functioning of nature is, and always has been, an untiring human endeavour. With the passing of time, and the testing of innumerable hypotheses, many biological processes are now fairly well understood. However, the integration of individual research efforts is essential if the behaviour of complex living organizations is to be comprehended. The concept of a systems approach is, at the present time, possibly the most suitable body of theory available for the integration of current knowledge on the basic principles of biological and bio-economic systems. The fundamentals of this concept and its methodological aspects were the subject of Part A of this thesis.

The project from which this thesis originated was envisaged as a framework within which physical experimentation could be integrated with a less conventional research technique - simulation. The field experiments dealt with in Chapters 3 and 4 (Part B of this thesis) and the simulation model described in Chapter 5, were aimed at achieving this objective. The development of this project helped to reveal areas of the real system in which knowledge was deficient and to define what questions were to be answered by the field experiments which were to be conducted on these areas. In addition, the simulation experiment provided the basis for demarcating a portion of the response surface, within which further experimentation with the real system might be worthwhile.

Some of the problems involved in using measurements of standing crop to determine the growth of a grazed plant community were discussed in Chapter 3. A related problem is that more frequent sampling than is possible with this method would be required to determine precisely the rates of growth and disappearance and the effect of the environment on these rates. It is suggested (as noted by Jeffery (1975)) that in order to obtain useful information for modelling purposes, it is the rates of change which need to be estimated, not the size of the state variables.

In the experiment described in Chapter 3, plant growth rates were estimated from direct measurement of net photosynthesis. The usual problems of within-treatment variability were also relevant to this experiment. To obtain more accurate estimates, one alternative would have been to increase the number of replicates but this was prevented by limitations of equipment. Another alternative would have been to reduce the time of measurement with the growth chamber. However, it is likely that this would have resulted in an increased error of measurement since, for the rest of the day, the rate of photosynthesis would have had to be estimated from a equation similar to that used by Vickery (1972). In future experiments, one way of solving this problem would be to take measurements _in situ_ with a portable apparatus (Hadley and Bliss 1964) over periods of time sufficiently long to ensure the collection of appropriate data. Nonetheless, the results from this experiment showed that pasture growth rates, on an annual basis, were not significantly affected by stocking rate; a conclusion with implications in the management of grazing systems.

One area of deficient knowledge detected during model development was that relating to the effects of grazing on grain production of winter cereals. The data needs of the model indicated that the weights of green material at different stages of crop development were the main variables to be measured in order to quantify this effect. They were also used for assessing system behaviour in response to distinct grazing practices (See Chapter 6). However, if the model predictions are to be applied in practice, the person who has to make the decisions will find it difficult to measure the size of the variables. It is likely that the decision-maker would be greatly aided by the development of more practical relationships, using for example estimates of crop height and tiller density as indicators of the weight of green herbage. It is also likely that specific relationships would have to be developed for different crop species and, perhaps, varieties.

The results from the two grazing experiments showed that grazing may not necessarily affect the rate of vegetative growth of the plant community - or regrowth after grazing, in the case of the crop. An important point to raise is that the management decision, on whether or not and how to graze, should be considered in relation to the final product aimed at. For example, the reproductive performance of the oats crop was significantly affected by grazing, suggesting that, within the context of this system, what is gained in terms of animal products, may well be lost by the reduction in grain production. As shown in the simulation experiment, crop grazing resulted in slightly smaller economic returns.

There is a finite limit to the number of grazing experiments that may be conducted within a region at any one time (White 1975). In this study, the use of a whole-farm model permitted the evaluation of a wide range of enterprises and these evaluations were made over a larger sample of seasons than would usually be possible in a field experiment. The description of such a model and its subsequent evaluation constitute Part C of this thesis.

One of the major problems in the development of the model proved to be the lack of suitable information for specifying some structural relationships that appeared to be important. This is a common feature of most simulation studies concerned with systems synthesis. Since time and financial limitations are likely to restrict the extent to which this information can be obtained by extensive experimentation, a compromise approach is to synthesize first an approximate relationship from the data available, with the assistance of other scientists who have specialized knowledge on the subject. This relationship can then be tested in the model and subsequently evaluated from the results obtained. Following this trial and error procedure, a better relationship can be developed and this may provide an insight into the critical experimental information needed for a full understanding of the process.

Models can be a complement to physical experiments insofar as they may indicate the areas in which to concentrate limited research funds. Those parameters to which model output is most sensitive will provide guidelines for further research. Although the predictions of this model were highly sensitive to stocking rate and level of cropping and the model indicated the optimal region in which these variables might most profitably be explored, the overriding conclusion from this simulation was that the grazing of a crop was unlikely to benefit the system at any levels of these variables.

The use of whole-farm models to quantify the benefits of alternative systems is particularly relevant to systems where the primary objective is profit maximization. In a grazing system where feed gaps are likely to occur, the introduction of extra inputs, though costly, might result in increased profitability. With few modifications the present model could be used to evaluate some alternative management policies for filling feed gaps, such as (i) the supplementation of ewes during winter in both pasture-only and pasture and cropping systems, and (ii) the allocation of land to a summer-growing legume.

It has been demonstrated that the model can be used for its intended purpose, that is to evaluate different management policies and provide the decision-maker with a quantitative basis for his decision. Although the model's insensitivity to certain management parameters may diminish its degree of reliability, the aid it can provide to the decision-making process is certainly better than none.

Since the advent of simulation, many arguments have been advanced for and against its use in agriculture. Some of these arguments seem to be directed towards the conclusion that physical experimentation and simulation are exclusive rather than complementary approaches. The former has always had its place in handling agricultural research problems and has certainly brought us a long way. As a complement, simulation offers a dynamic method of using the results of experiments in making decisions about whole systems. This method uses experimental results for what they were intended to be used and may help to solve some of the pressing problems that confront today's agriculturalists. The degree of success that can be achieved will ultimately depend on the objectives, judgement and skill of the individual directing the simulation.

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APPENDIX A

LISTING OF PROGRAM SSCFS (FORTRAN IV)

Simulation model of a mixed sheep-cropping system

```
      PROGRAM SSCFS(INPUT,OUTPUT,TAPE60=INPUT,TAPE61=OUTPUT,LU,TAPE30,
     *TAPE31,TAPE5)
      DIMENSION TIME(52),FODPLOT(52,4),PINTAKE(52,4),PLWTCH(52,2)
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,   SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDP,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/FOD/RAIN(52),TEMP(52),PANEVA(52)
      COMMON/CONS/C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
      COMMON/INIT/IIRUN,KYEAR,SLMTI(10,5),GPI(10,5),DPI(10,5),
     1WTSPI(10,5),FLEECEI(10,5),SNPI(5)
      COMMON/PESOS/CCROP,VCOST,CREPL,CRESTN,TCOST,VWOOL,VLAMBS,VGRAIN,
     *VPROD,GMARGN
 2000 FORMAT(1H1,///,1X,*WEEK IT   AP      GP      DP      AC     GC      D
     *C      SNP      SNC  WTSP WTSC  GEPPH  DEPPH  GECPH  DECPH  WTCHP   W
     *TCHC FLEECP LAMP LAMC *,/)
 2010 FORMAT(2X,2I3,6F7.0,2F8.0,2F5.1,6F7.3,F6.2,2F5.2)
 2020 FORMAT(         /,4X,*WEEK EVAPT  RAIN  SLMT  SLMT  TEMP  TFG   FLAI
     *GRMAX  GINC SENES  AMNT  GEP    DEP    FLAI GRMAX  GINC SENES  AMNT
     * GEC   DEC   DECAY *,/,
     *4X,               *                           FG                FAST
     *PAST   PAST  PAST  SEND                CROP  CROP  CROP  CROP  SEND
     *              RATE *,/)
 2030 FORMAT(5X,I3,3F6.1,F6.2,F6.1,2F6.2,2F6.0,F6.3,3F6.0,F6.2,2F6.0,
     *F6.3,3F6.0,F6.3)
 2040 FORMAT(/////,10X, * GRAIN YIELD = *,F8.0, * KG/HA *,//
     *10X,* GREEN HERBAGE REMOVED FROM CROP BY GRAZING = *,F8.0,*KG/HA*/
     */,10X, * WEIGHT OF FLEECE SHORN = *,F8.2, * KG *,/
     */,10X,*VALUE OF LIVEWEIGHT = *,F8.2, * $/HEAD *,/)
 2050 FORMAT(///,50X, * TABLE OF ECONOMIC VARIABLES FOR THIS RUN *,/
     *         /,50X,* $/HA *,60X,* $/HA *,/
     *         /,32X,*COST OF CROPPING =*,F6.2,10X,24X,*VALUE OF WOOL PROD
     *UCTION =*,F6.2,/,
     *         34X,*VARIABLE COSTS =*,F6.2,10X,24X,*VALUE OF LAMB PRODUC
     *TION =*,F6.2,/,
     *         29X,*COST OF REPLACEMENT =*,F6.2,10X,23X,*VALUE OF GRAIN PR
     *ODUCTION =*,F6.2,/,
     *         29X,*COST OF RESTORATION =*,F6.2,/
     *         38X,*TOTAL COST =*,F6.2,10X,23X,*VALUE OF TOTAL PRODUCTION
     *=*,F6.2,/
     *         /,55X,* GROSS MARGIN =*,F7.2,* $/HA*,)
C
C  MODEL TO SIMULATE USE OF GRAIN CROPS AS SOURCE OF FODDER
C
C
C  OBJECTIVE FUNCTION   PROFIT MAXIMISATION  (INITIALLY)
C
```

```
      WRITE(LP,2050)CCROP,VWOOL,VCOST,VLAMBS,CREPL,VGRAIN,CRESTN,TCOST,
     *VPROD,GMARGN
      CALL QUIPLOT(TIME,FODPLOT,-52,-4,14H*TIME (WEEKS)*,
     *16H*DM YIELD KG/HA*)
      CALL QUIPLOT (TIME,PINTAKE,-52,-4,14H*TIME (WEEKS)*,
     *19H*DM INTAKE KG/HEAD*)
      CALL QUIPLOT (TIME,PLWTCH,-52,-2,14H*TIME (WEEKS)*,
     *19H*LWT CHANGE KG/DAY*)
C   SET INITIAL VALUES FOR SOIL MOISTURE, GREEN AND DRY PASTURE,WEIGHT OF
C   ANIMALS AND FLEECE AS THOSE AT THE END OF PREVIOUS YEAR. SETS FOR
C   DIFFERENT STOCKING RATES, FRACTION OF CROP OR FRACTION OF SHEEP ON
C   CROP ARE STORED IN SEPARATE ARRAY LOCATIONS (ACCORDING TO IIRUN)
      SLMTI(KYEAR,IIRUN) = SLMT
      GPI(KYEAR,IIRUN) = GP
      DPI(KYEAR,IIRUN) = DP
      WTSPI(KYEAR,IIRUN) = (WTSP * SNP + (SNPI(IIRUN)-SNP)*50.0) / SNPI
     *(IIRUN)
      FLEECEI(KYEAR,IIRUN) = FLEECP
C READ NEW SET OF DATA
      GO TO 1
      END

      SUBROUTINE INITA
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,  SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/FOD/RAIN(52),TEMP(52),PANEVA(52)
      COMMON/CONS/C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
      COMMON/INIT/IIRUN,KYEAR,SLMTI(10,5),GPI(10,5),DPI(10,5),
     1WTSPI(10,5),FLEECEI(10,5),SNPI(5)
      DATA IRUN,IIRUN,KYEAR,K/0,0,0,0/
  100 FORMAT(4I4,5A10)
  200 FORMAT(3(10X,F10.2))
 1000 FORMAT (4(10X,I10)/4(10X,I10)/4(10X,F10.1)/4(10X,F10.2)/4(10X,
     *F10.1)/3(10X,F10.1)/4(10X,F10.0)/10X,I5,10X,F10.2)
 1010 FORMAT (16F5.0)
 1020 FORMAT(4(10X,F10.0))
 2000 FORMAT(///,50X, * MISCELLANEOUS DATA *,//,8I3,F9.1,10F7.2,F9.2,
     *2F7.2/5F8.0)
 2010 FORMAT (///,50X, * RAINFALL DATA *,//,(19F7.1))
 2011 FORMAT(///,50X, * TEMPERATURE DATA *,//,(19F7.1))
 2012 FORMAT(///,50X, * PAN EVAPORATION DATA * ,//,(19F7.1))
 2020 FORMAT (///,50X, * MISCELLANEOUS CONSTANTS *,//,15F7.3)
 2030 FORMAT(1H1,///,30X, * METEOROLOGICAL INPUT DATA FOR THIS RUN FROM
     *YEAR : *,A10,/)
 2031 FORMAT(1H1,///,30X,*RESULTS FOR IIRUN =*I5,* FOR YEAR :*,A10,/)
C   READ IN INITIAL VALUES FOR MODEL
      NCR = 60
      LP = 61
      IF(IIRUN.EQ.0) GOTO 10
      IF(IIRUN.EQ.ISNP) GOTO 20
      IIRUN = IIRUN +1
      READ(NCR,200) SNP,FRAC,FRACS
      SNPI(IIRUN) = SNP
```

```
C   SET UP INITIAL VALUES
      LP=61
    1 DO 2 I=1,18
    2 C(I)=0.0
      CALL INITA
      WRITE(LP,2000)
      WRITE (30,2020)
C   MAIN TIMING LOOP
      DO 10 NT=NTSTART,NTEND,NTINC
C   THE TIME INCREMENT IS ONE WEEK
C   IN THE INITIAL MODEL THE GROWTH OF PASTURE, CROP AND WEEDS
C   IS CONSIDERED TO HAVE THE SAME FORM SO THAT A COMMON ROUTINE
C   IS CALLED FROM SUBROUTINES CROP AND PASTURE
      CALL MANAGE
C   UPDATE PASTURE
      CALL PASTURE
C   UPDATE CROP (INCLUDES GROWTH OF WEEDS )
      IF(FRAC .GT. 0.0 .AND. NT .GE. NT2+2 .AND. IT .GE. 3
     * .AND. NT .LE. 36) CALL CROP
C   REDUCE PASTURE BY EATING
      CALL EATP
C   REDUCE PASTURE BY OTHER LOSSES
      CALL LOSSP
C   REDUCE CROP BY EATING ( INCLUDES EATING OF WEEDS )
      IF(SNC.NE.0.0)CALL EATC
C   TRANSFER OF PASTURE FROM GREEN TO DRY
      CALL AGEP
      IF(FRAC .GT. 0.0) CALL AGEC
      WRITE(LP,2010)NT,IT,AP,GP,DP,AC,GC,DC,SNP,SNC,WTSP,WTSC,GEPPH,
     *DEPPH,GECPH,DECPH,CLWCHP,CLWCHC,FLEECP,VALAMP,VALAMC
      WRITE(30,2030)NT,ACEVAT,RAIN(NT),SLMT,SLMTFG,TEMP(NT),TFG,FLAIP,
     *GRMAXP,GINCP,TGDP,AMTSNDP,GEP,DEP,FLAIC,GRMAXC,GINCC,TGDFC,AMTSNDC
     *,GEC,DEC,DECRATE
      TIME(NT)=NT
      FODPLOT(NT,1)=GP
      FODPLOT(NT,2)=DP
      FODPLOT(NT,3)=GC
      FODPLOT(NT,4)=DC
      PINTAKE(NT,1) = GEPPH
      PINTAKE(NT,2) = DEPPH
      PINTAKE(NT,3) = GECPH
      PINTAKE(NT,4) = DECPH
      PLWTCH(NT,1) = CLWCHP
      PLWTCH(NT,2) = CLWCHC
      TLAMB=TLAMB + (VALAMP*SRP+VALAMC*SRC)/(SRP+SRC)
C   ASHEEP ACCUMULATES WEKKLY NUMBER OF SHEEP TO ENABLE CALCULATION OF
C   AVERAGE CARRYING CAPACITY AT THE END OF THE RUN
      ASHEEP = ASHEEP + SNP + SNC
C   END OF MAIN LOOP
   10 CONTINUE
      CALL COMMENT
C   CALCULATE OBJECTIVE FUNCTION
      CALL FINANCE
      GMARGN = VPROD - TCOST
      WRITE(LP,2040)GRAIN,TOTREM,SHORN,TLAMB
```

```
      IF(KYEAR.EQ.1) GO TO 40
      SLMT = SLMTI (KYEAR-1,IIRUN)
      GP = GPI(KYEAR-1,IIRUN)
      DP = DPI(KYEAR-1,IIRUN)
      WTSP = WTSPI(KYEAR-1,IIRUN)
      FLEECP = FLEECEI(KYEAR-1,IIRUN)
      GO TO 30
   10 READ(NCR,100)IYEARS,ISNP,IFRAC,IFRACS,(NYEARS(K),K=1,5)
      READ(NCR,1000)NTSTART,NTEND,NTINC,NT1,NT2,NT3,NT4,NT5,CAP,CF,
     *DDC,DDP,DGC,DGP,DGW,FC,FP,FRACI,FRACSI,SNPI(1),TA,WTSPO,SLMTO,GPO,
     *GCO,DPO,DCO,LEVCROP,FLEECEO
      READ(NCR,1020)C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
   40 SLMT = SLMTO
      GP=GPO
      DP = DPO
      WTSP = WTSPO
      FLEECP = FLEECEO
      GC=GCO
      DC=DCO
      WTSC=0.0
      IF(KYEAR.EQ.1)GO TO 30
   20 KYEAR = KYEAR + 1
      READ(NCR,1010) (RAIN(I), I=1,52)
      IF (EOF(NCR)) 1,2
    2 READ(NCR,1010)(TEMP(I),I=1,52)
      READ(NCR,1010) (PANEVA(I),I = 1,52)
      SNP=SNPI(1)
      FRAC = FRACI
      FRACS = FRACSI
      IF (IIRUN .EQ. 0) GO TO 25
      SLMT=SLMTI(KYEAR-1,1)
      GP=GPI(KYEAR-1,1)
      DP=DPI(KYEAR-1,1)
      WTSP=WTSPI(KYEAR-1,1)
      FLEECP=FLEECEI(KYEAR-1,1)
   25 IIRUN = 1
C  INCREMENT COUNTER FOR YEAR NUMBER
      K = K+1
   30 CONTINUE
      AP = TA
      IT = 1
      NTS = 0.0
      TOTREM = 0.0
      TLAMB = 0.0
      DC = 0.0
      ASHEEP = 0.0
      WRITE(LP,2031) IIRUN,NYEARS(K)
      WRITE(30,2030) NYEARS(K)
C     WRITE(LP,2000)NTSTART,NTEND,NTINC,NT1,NT2,NT3,NT4,NT5,CAP,CF,DDC,
C    *DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,WTSP,SLMTO,GPO,GCO,DPO,DCO
C     WRITE(LP,2010) RAIN
C     WRITE(LP,2011)TEMP
C     WRITE(LP,2012) PANEVA
C     WRITE (LP,2020)C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
      RETURN
    1 STOP
      END
```

```
      SUBROUTINE MANAGE
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,   SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/FOD/RAIN(52),TEMP(52),PANEVA(52)
      COMMON/CONS/C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
C  THIS ROUTINE HANDLES THE CHANGES TO THE SYSTEM RESULTING FROM
C  THE VARIOUS STAGES OF CROP GROWTH. IT MOVES SHEEP AS APPROPRIATE
C  AND ALLOCATES LAND FOR CROP OR PASTURE
      GO TO(1,2,3,4,5,6)IT
C  CHECK FOR DATE OF LAND PREPARATION I.E. INITIATION OF CROPPING
    1 CONTINUE
      IF(NT.NE.NT1)RETURN
C  ESTABLISH AREA FOR CROPPING AND PASTURE
      AC = AP*FRAC
      AP = AP*(1.0-FRAC)
C     ENSURE THAT NO SHEEP ARE ON CROP AT THIS STAGE
      SNC = 0.0
C  SET INDEX FOR NEXT STAGE
      IT = 2
      RETURN
    2 CONTINUE
C     CHECK TO SEE IF CROP CAN BE SOWN AT THIS TIME
C  SET INITIAL AMOUNT OF WEEDS
C  FOR SUCCESSFUL GERMINATION SOIL MOISTURE MUST EXCEED WILTING POINT
C  (OWEN,1951)
      IF(NT .LT. NT2 .OR. SLMT .LE. 39.) RETURN
      SEED = 160.
      NGERM=NT+2
      GW = 0.0
      IT = 3
      RETURN
    3 CONTINUE
C  CHECK TO SEE IF CROP CAN NOW BE GRAZED
      IF(GC.LT.1250.)RETURN
      NT3 = NT
      SNC = SNP*FRACS
      SNP = SNP - SNC
      WTSC = WTSP
      FLEECC = FLEECP
      IT = 4
      RETURN
    4 CONTINUE
C GRAZING MANAGEMENT ROUTINE
C   VARIABLE LOSGRN(LOSS OF GRAIN) SETS 3 LEVELS OF LOSS (20,40 AND 70(),
C   WHICH ARE ALLOWED TO OCCUR IN ORDER TO FEED EITHER MORE SHEEP ON THE
C   CROP OR FOR A LONGER TIME
C   IF AVAILABILITY FALLS BELOW THE CORRESPONDING LEVEL(GRAIN .LE. LOSGRN)
C   GRAZING IS HALTED
```

```
      IF(LEVCROP .EQ. 2)       LOSGRN = 2850.5 * 0.8
      IF(LEVCROP .EQ. 3)       LOSGRN = 2850.5 * 0.6
      IF(LEVCROP .EQ. 4)       LOSGRN = 2850.5 * 0.3
      FINLAVL = GC
      GRAIN = 2850.5 * (1.-EXP(  -0.0013 * FINLAVL))
      IF(GRAIN .LE. LOSGRN) GO TO 350
C THIS MINOR ROUTINE IS INTENDED TO ADJUST SR DURING THE LAST TWO WEEKS
C   OF GRAZING SO THAT THE DESIRED AVAILABILITY AT THE END OF
C     GRAZING CAN BE OBTAINED
C     VARIABLE LEVCROP SETS 4 LEVELS
C                                              1 = UNGRAZED
C                                             2 = 1250 KG/HA (GREEN DM)
C                                              3= 750
C                                             4= 250
      IF(NT.NE.NT4-2) GO TO 300
      IF(LEVCROP.EQ.1)GO TO 350
      IF(LEVCROP.EQ.2)FINLAVL=1250.
      IF(LEVCROP.EQ.3)FINLAVL=750.
      IF(LEVCROP.EQ.4)FINLAVL=250.
      IF(GC.GT.FINLAVL) 250,300
  250 CONTINUE
      EXCESS=GC - FINLAVL
      SNC2 = (EXCESS+GINCC) / GEC * SRC * AC / 2.0
      IF(SNC2 .GT. SNP) SNC2=SNP
      FLEECC = (SNC2*FLEECP + SNC*FLEECC)/(SNC2+SNC)
      FLEECP = FLEECC
      WTSC = (SNC2*WTSP + SNC*WTSC)/(SNC2+SNC)
      SNC=SNC+SNC2
      SNP=SNP - SNC2
      IF(SNP .EQ. 0.0) WTSP=0.0
C     CHECK TO SEE IF GRAZING CROP SHOULD STOP (LENGTH OF GRAZING)
  300 IF(NT.NE.NT4) RETURN
  350 CONTINUE
      FINLAVL = GC
      WTSP =(SNP*WTSP + SNC*WTSC)/(SNP + SNC)
      FLEECP = (SNP*FLEECP + SNC*FLEECC)/(SNP + SNC)
      SNP = SNP + SNC
      SNC = 0.0
      SRC = 0.0
      WTSC = 0.0
      FLEECC = 0.0
       GEC = 0.0
       DEC = 0.0
      GECPH = 0.0
      DECPH = 0.0
      CLWCHC = 0.0
      VALAMC = 0.0
      IT = 5
      RETURN
    5 CONTINUE
C  CHECK FOR HARVEST DATE
      IF(NT.NE.NT5)RETURN
      CALL HARVEST
      IT = 6
      RETURN
    6 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE PASTURE
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,  SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/FOD/RAIN(52),TEMP(52),PANEVA(52)
      COMMON/CONS/C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
C
C
      G = GP
      F = FP
      CALL GROW(G,F,GPINC,0)
      GP = GP + GPINC
      RETURN
      END

      SUBROUTINE CROP
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,  SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/FOD/RAIN(52),TEMP(52),PANEVA(52)
      COMMON/CONS/C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
C
C
C     THIS ROUTINE KEEPS ACCOUNT OF CROP GROWTH FROM SEEDLING EMERGENCE
C     TILL FLOWERING (WEEK 36 : END OF OCTOBER FOR UNGRAZED CROP)
      IPHOT=NGERM+1
      IF(NT.GT.IPHOT) GO TO 20
      IF(NT .EQ. IPHOT)10,30
   10 CONTINUE
      GERM=0.95
C   FACTOR OF 4.0 BELOW TAKEN FROM WILLIAMS,R.F.(1960).HE REPORTED A FOURFOLD
C   INCREASE IN DRY WEIGHT OF SEEDLINGS AFTER 21 DAYS FROM SOWING
      GCO = SEED * GERM * 4.0
      GC=GCO
   20 G=GC
      F = FC
      CALL GROW (G,F,GCINC,1)
      GC = GC + GCINC
      IF(NT .EQ. 36) FLOWYLD = GC
C     G = GW
C     D = DW
C     CALL GROW(G,D,F,GWINC)
C     GW = GW + GWINC
   30 RETURN
      END
```

```
      SUBROUTINE GROW (G,F,GINC,NF)
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,   SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/FOD/RAIN(52),TEMP(52),PANEVA(52)
      COMMON/CONS/C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
C
C
C   CALCULATE THE GROWTH FOR THIS PERIOD FROM SEASONAL AND OTHER FACTORS
C   G=GREEN/HA   D=DRY/HA   GINC=GROWTH INCREMENT
C
C    CALCULATE POTENTIAL EVAPOTRANSPIRATION FROM PAN EVAPORATION
C   F = SEASONAL VARIATION OF POTENTIAL EVAPOTRANSP. (PENMAN,1948)
       IF (NF .EQ. 1) GO TO 10
      F = 0.7
      IF (NT .GT. 9) F = 0.6
      IF (NT . GE. 28) F = 0.7
      IF (NT .GT. 39) F = 0.8
C
C   ACTUAL EVAPOTRANSPIRATION FROM SOIL MOISTURE
C   ROOT ZONE DEPTH =  30 CM , FC = 28 PER CENT&  WP = 13 PER CENT
   10 FC = 84.
      WP = 39.
      ASLMT = FC - WP
       IF (NF .EQ. 1) GO TO 20
C   ACTUAL EVAPOTRANSPIRATION LT POTENTIAL IF SLMT LT 70 PER CENT
C   ASLMT (WARTENA AND VELDMAN, 1961)
C   DE ALVIM(1960) ,IF AVAILABLE WATER = 0.0,THEN ACTUAL = 0.1 POTENTIAL
      FSLMTO=SLMT+RAIN(NT)/2.
      IF ( FSLMTO .GE. FC) FSLMTO = FC
      FSLMT1 = ( FSLMTO - WP)/ASLMT * 100.
      EVRWB=F*(1.-EXP(-0.035*FSLMT1))
      IF (EVRWB .LE. 0.1) EVRWB = 0.1
C
C   UPDATE SOIL MOISTURE CONTENT
       ACEVAT = EVRWB * PANEVA(NT)
      SLMT = SLMT + RAIN(NT) - ACEVAT
   20 IF (SLMT .GE. FC) SLMT = FC
C
C   SOIL MOISTURE FACTOR FOR PASTURE GROWTH
C   SLMTFG = RATIO ACTUAL/POT.
       FSLMT2 =( SLMT-WP)/ASLMT * 100.
      SLMTFG=1.-EXP(-0.035*FSLMT2)
       IF(SLMTFG .LE. 0.1) SLMTFG = 0.1
```

```
C
C   TEMPERATURE FACTOR FOR GROWTH
C     NEW TFG USED FOR THESE RUNS(LOW TEMP HAVING MORE SEVERE EFFECT ON GROWTH)
      TFG = -0.5844 + 0.2268*TEMP(NT) - 0.0271*TEMP(NT)**2
     * + 0.00197*TEMP(NT)**3 - 0.000063*TEMP(NT)**4
     * + 0.00000068*TEMP(NT)**5
      IF(TFG .GT. 1.) TFG=1.
      IF(TEMP(NT) .LT. 4.)TFG=0.0
C
C   CALCULATE GROWTH INCREMENT (KG/HA /WEEK)
C   GRMAX/WEEK = K * W * ((GPMAX/W)**0.5 - 1.0) / 0.5
C   THE ESTIMATED GRMAX AT THE POINT OF INFLEXION FOR CALCULATING
C   K IN PASTURE EQUATION IS 150. KG/DAY
C   GROWTH RATE EQUATION AFTER F. J. RICHARD (1959)
       WEEK = NT
      IF (NF .EQ. 1) GO TO 30
C   SET PARAMETERS FOR PASTURE GROWTH
C   MAXIMUM CEILING YIELD FOR PASTURES IS 8000 KG/HA OF TOTAL DM
      CYMAX = 8000.
      GO TO 40
C   SET PARAMETERS FOR CROP GROWTH
C   MAXIMUM CEILING YIELD FOR CROP IS 12800  KG/HA OF TOTAL DM
C   MAXIMUM GROWTH RATE FOR CROP = 200 KG/HA (DE WIT)
   30 CYMAX = 10000.
C   CALCULATE ACTUAL CEILING YIELD IN RESPONSE TO LIGHT ENVIRONMENT, MAXIMUM
C   GROWTH RATE USING RICHARDS  EQUATION(1959) AND ACTUAL WEEKLY GROWTH RATE
C   AS FROM MAXIMUM AND ENVIRONMENTAL LIMITATIONS
   40 CLNYLD = CYMAX * (0.791 + 0.153 * SIN(0.121 * (WEEK+10.) + 1.25))
      GRMAX = 0.2625 * G * ((CLNYLD/G) ** 0.5 - 1.) / 0.5
      IF(NF .EQ. 1) GRMAX = 0.56 * G * ((CLNYLD/G)**(-1) - 1.0) / (-1.0)
      GINC = GRMAX * SLMTFG * TFG
      IF (NF .EQ. 1) GO TO 50
      GRMAXP = GRMAX
      GINCP = GINC
      GO TO 60
   50 GRMAXC = GRMAX
      GINCC = GINC
   60 RETURN
      END
```

```
      SUBROUTINE EATP
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,   SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/FOD/RAIN(52),TEMP(52),PANEVA(52)
      COMMON/CONS/C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
C
C
C     CALCULATE POTENTIAL INTAKE (KG DM/DAY/ANIMAL)
      W=WTSP
      U=W*(60- 0.6 * W)/1000.
C     EFFECT OF DIGESTIBILITY ON INTAKE
      APIDG = 2.0 * (1.0 - EXP(-(0.65 - ABS(DGP - 0.75))))
      APIDD = 2.0 * (1.0 - EXP(-(0.65 - ABS(DDP - 0.75))))
C     EFFECT OF AVAILABILITY ON INTAKE
      APIAG = 1.0 - EXP (-GP * DGP/700. )
      APIAD = 1.0 - EXP (-DP * DDP/ 700. )
C     CALCULATE TRUE INTAKE OF GREEN (KG DM/DAY/ANIMAL)
      GEPPH = U * APIDG * APIAG
C     POTENTIAL INTAKE OF DRY PASTURE
      UD = U - GEPPH
C     TRUE INTAKE OF DRY PASTURE
      DEPPH = UD * APIDD *APIAD
      DG = DGP
      DD = DDP
      NW = 0
      SRP=SNP/AP
      IF(SNP .EQ. 0.0) GO TO 10
      CALL WEIGHT (W,DG,DD,GEPPH,DEPPH,NW)
      WTSP = W
C     UPDATE GREEN AND DRY PASTURE ACCORDING TO GREEN/DRY EATEN
   10 GEP=GEPPH*SRP*7.
      DEP=DEPPH*SRP*7.
      GP = GP - GEP
      DP = DP - DEP
      RETURN
      END
```

```
      SUBROUTINE EATC
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,   SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDP,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/FOD/RAIN(52),TEMP(52),PANEVA(52)
      COMMON/CONS/C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
C
C
      W = WTSC
C     POTENTIAL INTAKE (KG/DM/DAY)
      U= W * (60. - 0.6 * W)/1000.
C     ADJUST FOR DIGESTIBILITY
      APIDG = 2.0 * (1.0 - EXP(-(0.65 - ABS(DGC - 0.75))))
      APIDD = 2.0 * (1.0 - EXP (-(0.65 - ABS(DDC - 0.75))))
C     ADJUST FOR AVAILABILITY
      APIAG = 1.0 - EXP(-GC * DGC/700.)
      APIAD = 1.0 - EXP(-DC * DDC/700.)
C     TRUE INTAKE (KG DM/DAY)OF GREEN
      GECPH = U * APIDG * APIAG
C     POTENTIAL INTAKE OF DRY
      PDE = U - GECPH
C     TRUE INTAKE OF DRY PASTURE
      DECPH = PDE * APIDD * APIAD
      DG = DGC
      DD = DDC
      NW = 1
      SRC = SNC/AC
      CALL WEIGHT (W,DG,DD,GECPH,DECPH,NW)
      WTSC = W
C     AMMOUNT OF GREEN/DRY EATEN FROM CROP
      GEC = GECPH*SRC*7.
      DEC = DECPH * SRC * 7.
      GC = GC - GEC
      DC = DC - DEC
C   COMPUTE TOTAL AMOUNT OF HERBAGE EATEN BY SHEEP DURING PERIOD OF CROP
C   GRAZING IN KG DM/HA (GREEN)
      TOTREM = TOTREM + GEC
      RETURN
      END
```

```
      SUBROUTINE LOSSP
C   LOSSES OTHER THAN EATING
C
C
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,   SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/FOD/RAIN(52),TEMP(52),PANEVA(52)
      COMMON/CONS/C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
C
C
      IF(SLMT .LT. 39.) SLMT=39.
C
C   INFLUENCE OF SOIL MOISTURE ON DECAY RATE
      SLMTFD=0.0189*SLMT-0.587
C
C   EFFECT OF TEMPERATURE ON DECAY
      TEMPFD=1.-EXP(-0.0174*TEMP(NT)**2)
C
C   DECAY RATE INCREASES AS AMOUNT OF TOTAL HERBAGE (GREEN + DRY) DOES.
C   THE RATE IS DOUBLED WHEN TOTAL DM .GE. 7000 KH/HA (FACTOR RANGES FROM 1-2)
      AMONTFD = 0.99 + 1.03 * (1. - EXP(-0.068 * ((GP+DP)/1000.)**2))
C
C   MAXIMUM WEEKLY DECAY RATE=0.08 AT SLMT=FC AND TEMP .GE.
C   18 CENTIGRADES + INCREASE DUE TO TOTAL DM PRESENT
      DECRATE = 0.08 * SLMTFD * TEMPFD * AMONTFD
      DP=DP*(1.-DECRATE)
      RETURN
      END
```

```
      SUBROUTINE AGEP
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,  SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/FOD/RAIN(52),TEMP(52),PANEVA(52)
      COMMON/CONS/C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
C
C
C   REDUCE GREEN BY THE FRACTION ASF * TGDF=MULTIPLE FACTOR INCLUDING
C   LAI,TEMP. AND SOIL MOISTURE EFFECTS ON SENESCENCE
C
C   1/12(WEEK 40) FLOWERING STARTS. TEMP AND DRYING OF THE SOIL
C   ACCELERATE RATE OF SENESCENCE ,THE DEGREE OF INFLUENCE BEING
C   LARGER THAN THAT DURING THE VEGETATIVE PERIOD.
C   SOIL MOISTURE STRESS BECOME EVIDENT WHEN WATER POTENTIAL
C   .LE. -3.5 BARS (MCWILLIAM,1968)
       IF(NT.LT.40.OR.NT.GE.49) GO TO 20
       IF(NT.LT.44.AND.SLMT.LT.49.5) GO TO 10
       IF(NT.GE.44.AND.NTS.LT.5) GO TO 10
       GO TO 20
   10  NTS=NTS+1
       IF(NTS.LT.4.OR.NTS.GT.5) GO TO 20
       WEEK=NTS
       TGDF=0.5*WEEK-1.55
       DP=DP+GP*TGDF
       AMTSNDP=GP*TGDF
       GP=GP*(1.0-TGDF)
       RETURN
   20  AFS=1.0
       IF(GP.LE.1500.)AFS=0.00067*GP
       TGDF=(1.-0.99*SLMTFG)*(1.-EXP(-0.003*TEMP(NT)**2))
       AMTSNDP=GP*AFS*TGDF
       GP=GP-AMTSNDP
       DP=DP+AMTSNDP
       RETURN
       END
```

```
      SUBROUTINE AGEC
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,   SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/FOD/RAIN(52),TEMP(52),PANEVA(52)
      COMMON/CONS/C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
C
C     AFS AND TGDFC = SAME FACTORS AS USED FOR PASTURE IN SUBROUTINE AGEP.
C     THEY CALCULATE WEEKLY RATE OF CROP SENESCENCE UNTIL FLOWERING.
C     AS FROM FLOWERING WEEKLY RATE OF CROP SENESCENCE INCREASES TO 15%
C
      AFS=1.0
      IF(GC .LE. 1500.) AFS=0.00067*GC
      TGDFC = (1.-0.99*SLMTFG) * (1.-EXP(-0.003 * TEMP(NT)**2))
      IF(NT.GT.36)TGDFC=0.15
      AMTSNDC=GC*AGC*TGDFC
      GC=GC-AMTSNDC
      DC =DC+AMTSNDC
      RETURN
      END

      SUBROUTINE HARVEST
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,   SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/FOD/RAIN(52),TEMP(52),PANEVA(52)
      COMMON/CONS/C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
C
C
C  THIS SUBROUTINE CALCULATES GRAIN YIELD AS A FUNCTION OF GREEN DM AT THE END
C  OF GRAZING(FINLAVL) AND GREEN DM AT FLOWERING(FLOWYLD) BY MEANS OF THE
C  FOLLOWING MULTIPLE REGRESSION EQUATION
C                                        Y = A + B1*X1 + B2*X2
C  THE PARAMETERS A,B1 AND B2 WERE DERIVED FROM THE 1974 CROP GRAZING-EXPERIMENT
C  DATA FOR OATS
      GRAIN = 399.93 + 0.1792*FINLAVL + 0.1959*FLOWYLD
      STUBBLE = (GC+DC) - GRAIN
      GC = 0.0
      DC = STUBBLE
      RETURN
      END
```

```
      SUBROUTINE WEIGHT (W,DG,DD,GE,DE,NW)
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,   SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
C     DIGESTIBLE FOOD EATEN (KG/DOM/ANIMAL/DAY)
      DFUE = GE*DG+DE*DD
C     DIGESTIBLE ENERGY INTAKE IN KCAL/DAY
      DEI = DFUE * 4.4 * 1000.
      CMEI = DEI * 0.81
C     MAINTENANCE REQUIREMENTS (KCAL ME/DAY)
      EMR = 132. * W ** 0.75
      EB = CMEI - EMR
C     DAV = AVERAGE DIGESTIBILITY OF GREEN + DRY
      DAV = DFUE/(GE + DE)
      IF (EB.GT.0.0) GO TO 50
      GO TO 51
C     CALCULATE LIVEWEIGHT GAIN (KG/ANIMAL/DAY)
C     PMEF = METABOLIZABLE ENERGY OF FOOD AS PERCENTAGE OF GROSS ENERGY
   50 PMEF = 4.4 * DAV * 0.81/4.4
      VMEP = 0.81 * PMEF + 0.03
C     (W - 20.) * 0.143 + 2.72  = CALORIFIC VALUE OF LIVEWEIGHT CHANGE (MCAL/KG)
      CLWCH = VMEP*EB/(((W-20.) * 0.143 + 2.72) * 1000.)
      GO TO 52
C     CALCULATE LIVEWEIGHT LOSS
   51 VMEM = 0.83
      CLWCH = EB/(((W - 20.)* 0.143 + 2.72) * 1000. * VMEM)
C     FINAL WEIGHT FOR THAT WEEK (KG)
   52 W = W + CLWCH * 7.
      IF(NW .EQ.0) CLWCHP = CLWCH
      IF(NW.EQ.1) CLWCHC = CLWCH
      CALL WOOL (CMEI,NW)
      IF(NW.EQ.0) VALAMP = VALAMB(W)
      IF(NW.EQ.1) VALAMC = VALAMB(W)
C  CALCULATE COEFFICIENT OF MORTALITY(CDTH) AS A FUNCTION OF LWT
C  (YY = EXP(-C*X) BELOW CRITICAL WEIGHT(35 KG, FROM ARNOLD G.W., AJEAAH 11,1971)
C  THIS COEFF RANGES FROM 0.0 TO 1.0 FOR LWT BETWEEN 35. AND 25. KG
      IF(W .GE. 35.0) GO TO 100
      CDTH = EXP(-0.45 * (W-25.))
      IF(W .LE. 25.0) CDTH=1.0
C  READJUST SHEEP NUMBER
      IF(NW .EQ. 0) SNP = SNP * (1.-ABS(CDTH))
      IF(NW .EQ. 1) SNC = SNC * (1.-ABS(CDTH))
      SRP = SNP/AP
      SRC = SNC/AC
C  READJUST MEAN LWT OF SHEEP ON THE ASSUMPTION THAT THOSE WHICH DIE HAVE
C  A MEAN LWT 5 KG LOWER THAN THE ACTUAL MEAN LWT
      IF(W .LE. 25.0) GO TO 100
      W = W + 5.0*CDTH
  100 RETURN
      END
```

```
      SUBROUTINE WOOL(CMEI,NW)
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,  SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
C
C  THIS SUBROUTINE CALCULATES DAILY WOOL GROWTH IN KG/SHEEP/DAY (CLEAN WOOL)
C  AS A FUNCTION OF THE METABOLIZABLE ENERGY INTAKE
C
C     FIRST CONVERT MEI FROM KCAL/DAY TO MJOULES/DAY
C     MJOULES = 4.184 * 10**-3 KCAL
      WMEI = CMEI * 4.184 / 1000.
C     CALCULATE DAILY WOOL GROWTH
      WOOLDAY = 0.001 * WMEI * (1.5 - 0.037*WMEI)
C     CALCULATE FLEECE WEIGHT AT THE END OF THE WEEK(KG)
      IF(NW .EQ. 0) FLEECE=FLEECP
      IF(NW .EQ. 1) FLEECE=FLEECC
      FLEECE = FLEECE + WOOLDAY * 7.
      IF(NW .EQ. 0) FLEECP=FLEECE
      IF(NW .EQ. 1) FLEECC = FLEECE
C     CHECK FOR SHEARING TIME (FIRST WEEK IN DECEMBER)
      IF(NT .NE. 40) GO TO 10
      SNSHON = SNP
      SHORN = FLEECP - 0.1
      FLEECP = 0.1
   10 RETURN
      END

      FUNCTION VALAMB(ACTWT)
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,  SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
      DIMENSION OPTWT(52),VALWT(52)
      DATA(OPTWT(IW),IW=1,52) /3*50.0,49.6,49.1,48.7,48.2,47.8,47.3,46.9
     *,46.4,46.0,45.5,45.0,46.0,47.0,48.0,49.0,50.0,51.0,52.0,53.0,54.0,
     *55.0,14*55.0,53.6,52.1,50.7,49.3,47.9,46.4,45.0,45.7,46.4,47.1,
     *47.9,48.6,49.3,50.0/
      DATA(VALWT(IV),IV=1,52) /3*0.18,15*0.13,6*0.25,14*0.25,14*0.04/
      IW = NT
      IV = NT
      WTF = (ACTWT-35.0)/(OPTWT(IW)-35.0)
      IF(ACTWT .LT. 35.0) WTF = 0.0
      IF(WTF.GT.1.0) WTF = 1.0
      VALAMB = WTF * VALWT(IV)
      RETURN
      END
```

```
      SUBROUTINE COMMENT
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,  SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDP,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/TIME/IT,NT,NT1,NT2,NT3,NT4,NT5,NTSTART,NTEND,NTINC,
     1NYEARS(10)
      COMMON/INIT/IIRUN,KYEAR,SLMTI(10,5),GPI(10,5),DPI(10,5),
     1WTSPI(10,5),FLEECEI(10,5),SNPI(5)
C
C
      DATA (IRUN = 0)
22010 FORMAT(1H1,5(/),30X,*RUN NUMBER*,I5,///,
     1       32X,  *ALLOCATION OF LAND*,/,
     1       30X,   *TOTAL AREA AVAILABLE*,F8.0,/,
     2       19X,   *FRACTION OF AREA USED FOR CROPS*,F8.2,/,
     3       34X,   *AREA FOR PASTURE*,F8.0,/,
     4       36X,   *AREA FOR CROPS*,F8.0,//,
     5       30X,   *MANAGEMENT PARAMETERS*,/,
     6       18X,   *LAND FOR CROPS SET ASIDE ON WEEK*,I6,/,
     7       32X,   *CROPS SOWN ON WEEK*,I6,/,
     8       24X,  *CROP GRAZING BEGUN ON WEEK*,I6,*   WHEN AVAILABILITY
     *BECOMES .GE. 1250. KG GREEN DM/HA*,/,
     9       24X,   *CROP GRAZING ENDED ON WEEK*,I6,/,
     1       28X,   *CROP HARVESTED ON WEEK*,I6,//,
     2       29X,  *ALLOCATION OF ANIMALS*,/,
     3       29X,  *TOTAL NUMBER OF SHEEP*,F8.0,/,
     3       18X,  *INITIAL STOCKING RATE ON PASTURE*,F10.2,* SHEEP/HA*,/
     4       13X,  *FRACTION OF ANIMALS INITIALLY ON CROP*,F10.2,/,
     5       21X,   *INITIAL STOCKING RATE ON CROP*,F10.2,*  SHEEP/HA*,/)
      IRUN = IRUN + 1
      CAC = TA*FRAC
      IF (FRAC .EQ. 0.0) GO TO 10
      SRCI = SNPI(IIRUN) * FRACS/CAC
   10 SRPI = SNPI(IIRUN)/TA
      WRITE(LP,2010)IRUN,TA,FRAC,AP,CAC,NT1,NT2,NT3,NT4,NT5,SNPI(IIRUN),
     *SRPI,FRACS,SRCI
      RETURN
      END
```

```
      SUBROUTINE FINANCE
      COMMON/MISC/CAP,CF,DDC,DDP,DGC,DGP,DGW,FC,FP,FRAC,FRACS,SNP,TA,
     1WTSP,GEP,DEP,GEC,DEC,GEW,GP,DP,GC,DC,GW,DW,AP,AC,WTSC,OF,SNC,
     2FUE,DFUE,U,SLMT,SLMTFG,NTS,DECRATE,LP,   SEED,NGERM,TOTREM,GRAIN,
     3LEVCROP,ACEVAT,TFG,FLAIP,FLAIC,SHORN,SNSHON,VALAMP,VALAMC,TLAMB,
     4SRP,SRC,FLOWYLD,ASHEEP
      COMMON/ZERO/C(1),GRMAXP,GRMAXC,GINCP,GINCC,FINLAVL,CLWCHP,CLWCHC,
     1GEPPH,DEPPH,GECPH,DECPH,TGDF,TGDFC,AMTSNDP,AMTSNDC,FLEECP,FLEECC
      COMMON/INIT/IIRUN,KYEAR,SLMTI(10,5),GPI(10,5),DPI(10,5),
     1WTSPI(10,5),FLEECEI(10,5),SNPI(5)
      COMMON/PESOS/CCROP,VCOST,CREPL,CRESTN,TCOST,VWOOL,VLAMBS,VGRAIN,
     *VPROD,GMARGN
      DATA CULT,PSEED,HAVEST,PSHEAR,PREPL,PRESTN,PVCOST /10.73,0.075,
     *14.81,0.40,8.05,25.0,3.00/
      DATA PWOOL,PGRAIN /2.50,0.075/
C
C  CALCULATE COSTS
      CSOWIN = (CULT+SEED*PSEED) * AC/TA
      CFERT = FC * CF * AC/TA
      CCROP = (CSOWIN + CFERT) + HAVEST * AC/TA
      CSHEAR = PSHEAR * SNSHON/TA
      VCOST = PVCOST * (ASHEEP/52.0) / TA + CSHEAR
      CREPL = SNPI(IIRUN) * 0.20/TA * PREPL
      CRESTN = (SNPI(IIRUN) - SNP) /TA * PRESTN
C  CALCULATE TOTAL COST
      TCOST = CCROP + VCOST + CREPL + CRESTN
C  CALCULATE TOTAL PRODUCTION
      VWOOL = SHORN * SNSHON /TA * PWOOL
      VLAMBS = TLAMB * SNP/TA
      VGRAIN = GRAIN * PGRAIN * AC/TA
      VPROD = VWOOL + VLAMBS + VGRAIN
      GMARGN = VPROD - TCOST
      RETURN
      END
```

APPENDIX B

GLOSSARY OF VARIABLE NAMES USED IN THE COMPUTER PROGRAM

AC	Area of crop (ha)
ACEVAT	Weekly rate of actual evapotranspiration (mm)
AFS	Upper limit to proportion of green herbage becoming senescent each week
AMONTFD	Factor for correcting decay rate for amount of herbage
AMTSNDC	Weekly amount of crop herbage senesced (kg DM ha^{-1})
AMTSNDP	Weekly amount of pasture herbage senesced (kg DM ha^{-1})
AP	Area of pasture (ha)
APIAD	Factor for correcting potential intake of dry herbage for availability
APIAG	Factor for correcting potential intake of green herbage for availability
APIDD	Factor for correcting potential intake of dry herbage for digestibility
APIDG	Factor for correcting potential intake of green herbage for digestibility
ASHEEP	Accumulated weekly number of sheep
ASLMT	Available soil moisture (mm)
C1	Constants
CAP	Capital ($)
CCROP	Total cost of cropping ($ ha^{-1} of whole farm)
CDTH	Rate of ewe mortality
CF	Cost of fertilizer ($ kg^{-1})
CFERT	Cost of fertilization ($ ha^{-1})
CLNYLD	Actual ceiling yield as determined by the light environment (kg ha^{-1})
CLWCHC	Liveweight change of ewes grazing the crop (kg)
CLWCHP	Liveweight change of ewes grazing the pasture (kg)

CMEI	Metabolizable energy intake (kcal day^{-1} $head^{-1}$)
CREPL	Cost of replacement ($)
CRESTN	Cost of mortality ($)
CSHEAR	Cost of shearing ($)
CSOWIN	Cost of sowing ($)
CYMAX	Maximum ceiling yield (observed data) (kg ha^{-1})
DAV	Average digestibility of diet
DC	Amount of dry crop (kg ha^{-1})
DDC	Digestibility of dry crop
DDP	Digestibility of dry pasture
DEC	Dry eaten on crop (kg ha^{-1})
DEI	Digestible energy intake (kcal day^{-1} $head^{-1}$)
DEP	Dry eaten on pasture (kg ha^{-1})
DECPH	Dry eaten on crop per head (kg)
DECRATE	Rate of decay (kg ha^{-1} $week^{-1}$)
DEPPH	Dry eaten on pasture per head (kg)
DFUE	Digestible food units eaten/sheep (kg)
DGC	Digestibility of green crop
DGP	Digestibility of green pasture
DP	Amount of dry pasture (kg ha^{-1})
DPI	Initial amount of dry pasture (1st week of the 10-year period during which the model was run) (kg ha^{-1})
EB	Energy balance of the animal (kcal day^{-1})
EMR	Energy requirements for maintenance (kcal day^{-1})
FC	Amount of fertilizer on crop (kg ha^{-1})
FC	Field capacity (in Subroutine GROW) (mm)
FINLAVL	Green herbage remaining on crop at the end of grazing
FLEECC	Fleece weight of ewes grazing on crop (kg)

FLEECI	Initial weight of fleece (kg)
FLEECP	Fleece weight of ewes grazing on pasture (kg)
FLOWYL	Yield of green herbage on crop at flowering (kg ha^{-1})
FRAC	Fraction of total farm area reserved for crops (management parameter)
FRACS	Fraction of total number of sheep to be fed on crop (management parameter)
GC	Amount of green crop (kg ha^{-1})
GEC	Green eaten on crop (kg ha^{-1})
GEP	Green eaten on pasture (kg ha^{-1})
GECPH	Green eaten on crop per head (kg day^{-1})
GEPPH	Green eaten on pasture per head (kg day^{-1})
GINCC	Actual rate of crop growth (kg ha^{-1} $week^{-1}$)
GINCP	Actual rate of pasture growth (kg ha^{-1} $week^{-1}$)
GMARGN	Gross margin per hectare ($)
GP	Amount of green pasture (kg ha^{-1})
GPI	Initial amount of green pasture (1st week)
GRAIN	Grain yield (kg ha^{-1})
GRMAXC	Maximum rate of crop growth (kg ha^{-1} $week^{-1}$)
GRMAXP	Maximum rate of pasture growth (kg ha^{-1} $week^{-1}$)
IT	Time index for state of crop (see NT1, NT2, etc.)
LEVCRP	Set levels of crop availability at the end of grazing
NT	Time (weeks)
NT1	START of land preparation
NT2	Sowing of crop
NT3	Commencement of crop grazing
NT4	End of crop grazing (management parameter)
NT5	Harvesting

NTEND	End date for the simulation (week number)
NTINC	Increments in time (weeks)
NTSTART	Starting date for the simulation (week number)
NYEARS	Number of years for the simulation
PANEVA	Weekly pan evaporation (mm)
PMEF	Metabolizable energy of food as percentage of gross energy
RAIN	Weekly rainfall (mm)
SEED	Rate of sowing for the crop (kg ha^{-1})
SHORN	Weight of fleece shorn (kg)
SLMT	Soil moisture content (mm)
SLMTFG	Factor for correcting rate of plant growth for soil moisture content
SLMTFD	Effect of soil moisture on decay rate
SLMTI	Initial soil moisture content (1st week) (mm)
SNC	Number of sheep on crop
SNP	Number of sheep on pasture
SNPI	Initial number of sheep on farm
SNSHON	Number of sheep shorn
SRC	Stocking rate on crop (sheep ha^{-1})
SRP	Stocking rate on pasture (sheep ha^{-1})
STUBBLE	Amount of crop remaining after harvest (kg ha^{-1})
TA	Total area of farm (ha)
TCOST	Total costs (\$ ha^{-1})
TEMP	Mean weekly temperature (^{o}C)
TEMPFD	Effect of temperature on decay rate
TFG	Factor for correcting rate of plant growth for temperature
TGDF	Rate of senescence (kg ha^{-1} $week^{-1}$)
TLAMB	Annual value of lamb production (\$ $head^{-1}$)
TOTREM	Total amount of herbage removed from crop by grazing (kg ha^{-1})

U	Ultimate level of intake (kg DM day^{-1})
UD	Potential intake of dry herbage (kg DM day^{-1})
VALAMC	Weekly value of lamb production on crop (\$ $head^{-1}$)
VALAMP	Weekly value of lamb production on pasture (\$ $head^{-1}$)
VCOST	Variable costs (\$ ha^{-1})
VGRAIN	Value of grain production (\$ ha^{-1})
VLAMBS	Economic value of lamb production (\$ ha^{-1})
VMEM	Value of metabolizable energy for maintenance
VMEP	Value of metabolizable energy for liveweight gain
VPROD	Total production per unit area of farm (\$)
VWOOL	Value of wool production (\$ ha^{-1})
WOOLDAY	Wool growth rate (kg $head^{-1}$ day^{-1})
WP	Wilting point (mm)
WTF	Ratio of actual to optimum ewe liveweight
WTSC	Average weight of sheep on crop (kg)
WTSP	Average weight of sheep on pasture (kg)

APPENDIX C

PROCEDURE FOR DERIVING THE VALUE OF THE CONSTANT 'K' IN THE GROWTH RATE FORMULA, FOR THE PASTURE AND THE CROP

The growth function proposed by Richards (1959) was used in the model to estimate plant growth rate. The general form of the equation is shown below:

$$\frac{dw}{dt} = k.w\ [(A/w)^{1-m}-1]/(1-m)$$

where A = maximum size attainable

w = weight of herbage

For the pasture growth rate formula a value of m = 0.5 was used. Therefore;

$$\frac{dw}{dt} = k.w\ [(A/w)^{0.5}-1]/0.5$$

The value of the constant k can then be calculated as:

$$k = \frac{\frac{dw}{dt} \cdot 0.5}{w.(\sqrt{A/w} - 1)} \qquad (1)$$

Assuming values of A = 8000 (ceiling yield for the pasture in kg ha^{-1}, Brougham 1959) and $\frac{dw}{dt}$ = 1260 (maximum weekly growth rate in kg ha^{-1}); w is calculated as $w = A.m^{1/1-m}$ and represents the weight of herbage at which $\frac{dw}{dt}$ maximizes. Substituting these values into equation (1) above:

$$k = 0.2625$$

For the crop, the logistic function was used with a value of m = 2, the original Richards' function then becoming:

$$\frac{dw}{dt} = k.w\ [(A/w)^{-1}-1]/-1$$

Therefore:

$$k = \frac{\frac{dw}{dt} \cdot (-1)}{w.(w/A-1)} \qquad (2)$$

Substituting 10000 (ceiling yield for the crop in kg ha^{-1}, Watson *et al.* 1963) for A, 1400 (maximum weekly growth rate in kg ha^{-1}) for $\frac{dw}{dt}$ and 5000 (kg) for w into equation (2) above:

$$k = 0.56$$